

DATA REDUCTION AND
CALIBRATION FOR SYNTHESIS
IMAGING

Tom Armstrong
Naval Research Lab
and NPOI

OUTLINE

- Planning the observations
- Calibration
- Model fitting / imaging
- Current capabilities and limitations
- Future developments with phase closure
- Exciting astrophysics

Planning the Observations

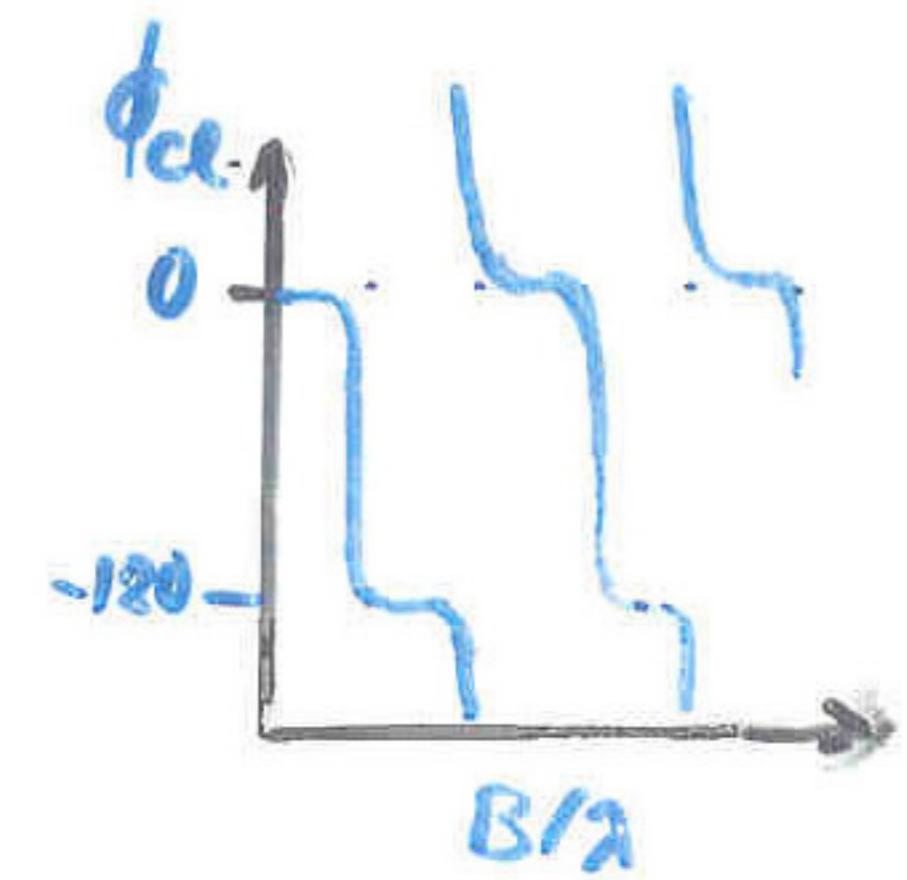
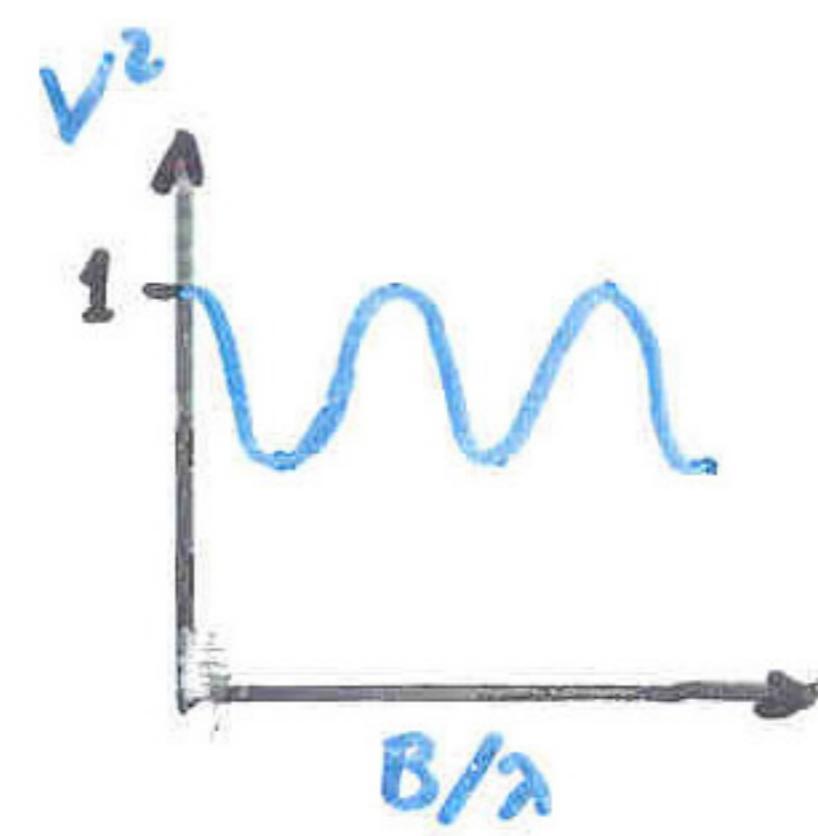
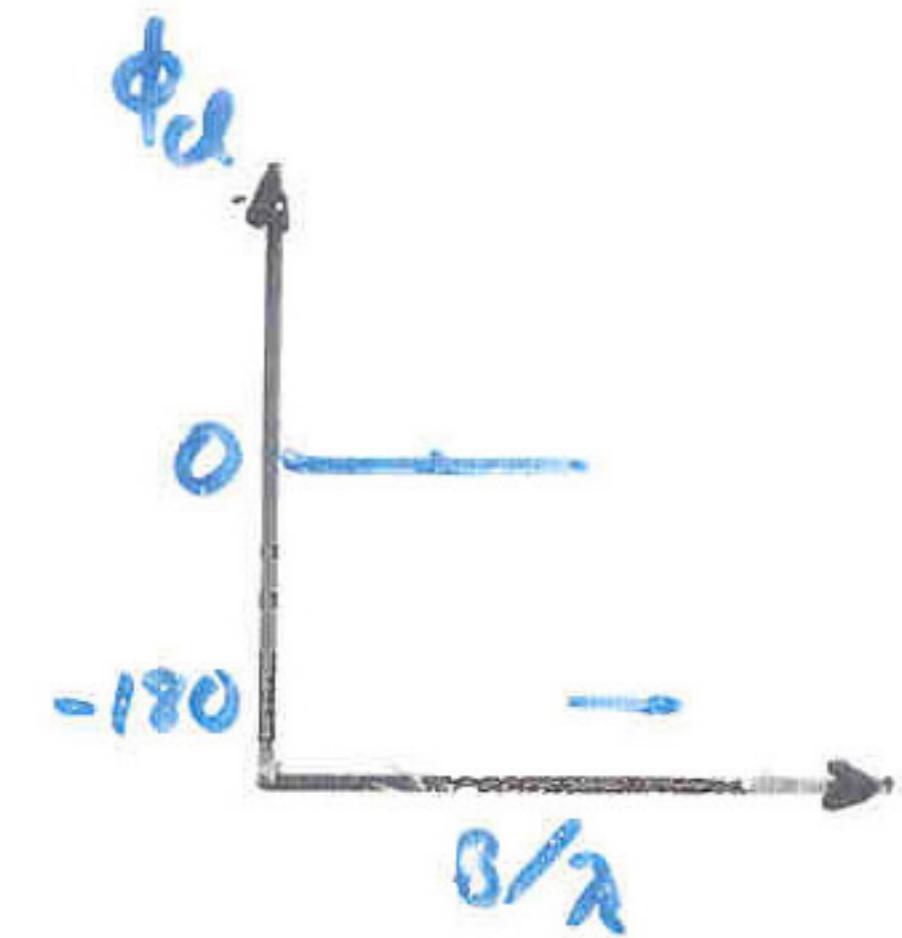
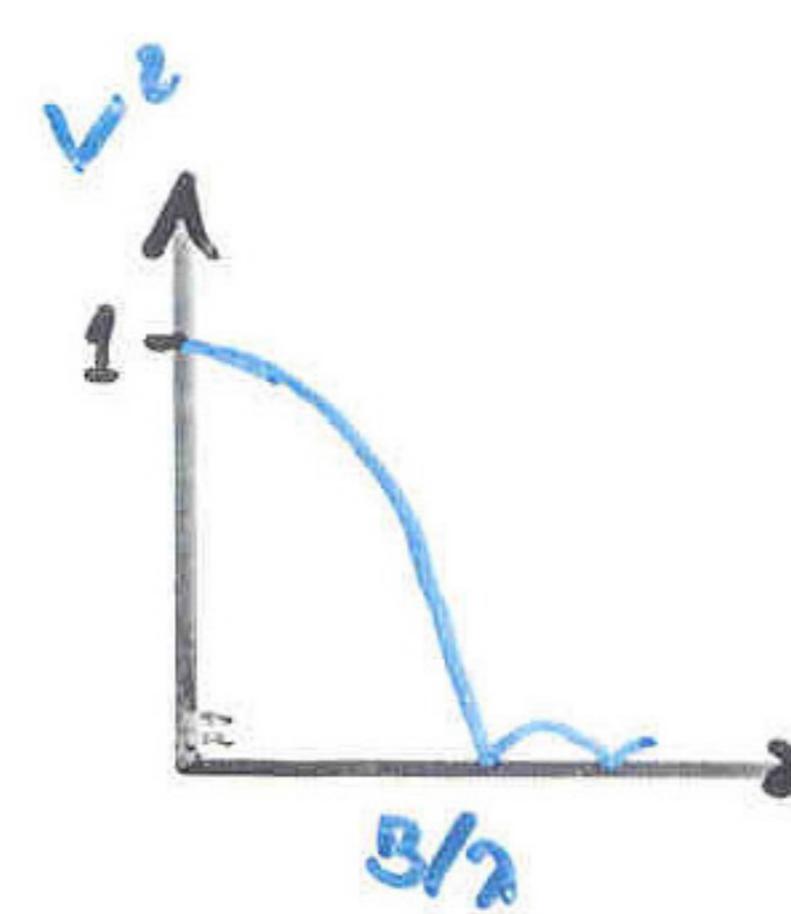
- Get the appropriate u-v coverage
 - Choose array configuration
 - Baseline lengths appropriate to angular scale of object
 - Each array element must be part of at least one baseline that will give detectable fringes
 - Distribute scans over enough time to give adequate u-v coverage
- Get enough phase calibrator scans to monitor seeing changes

What u-v coverage is needed?

- What are you trying to measure or image?
 - Single star diameter
 - Binary star separation
 - Extended source imaging
 - Stellar surface structure imaging

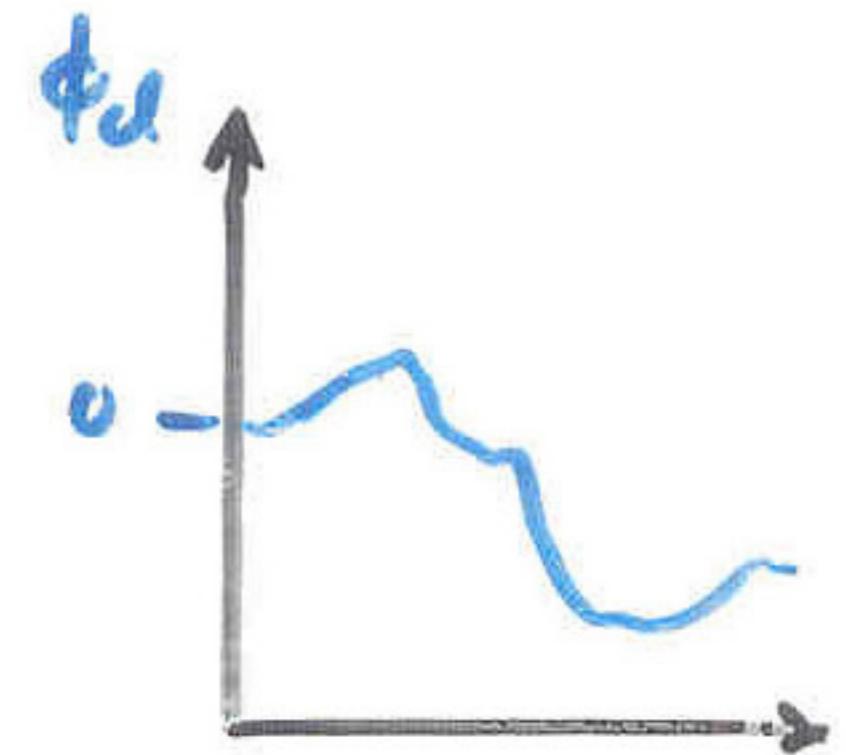
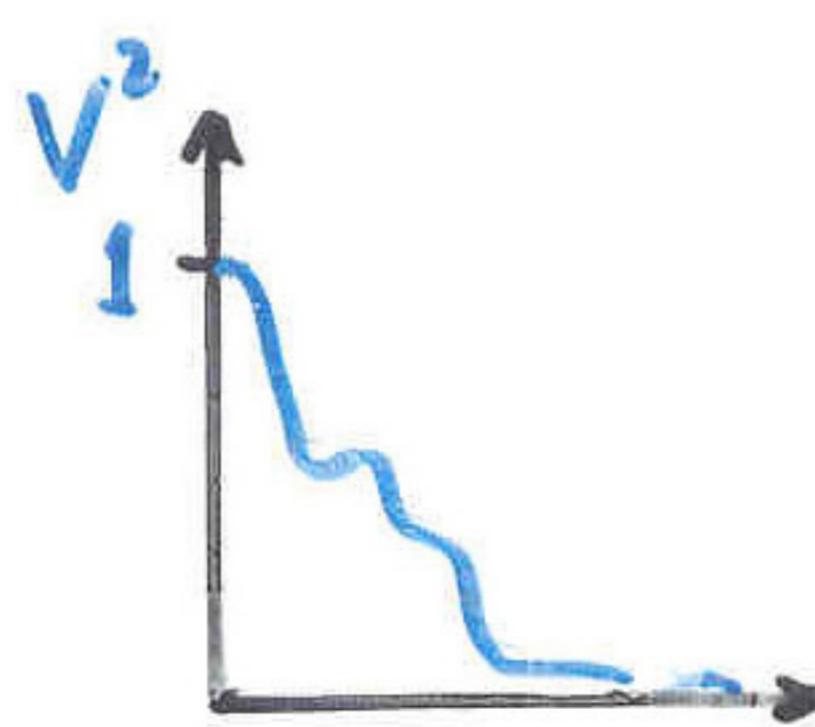
Different arrays for different sources

- Measuring a diameter: Baseline length close to first null (but not too close if it's a single-channel interferometer)
- Measuring a binary separation: Cross a couple V^2 maxima, either azimuthally (earth rotation) or radially (bandwidth synthesis)

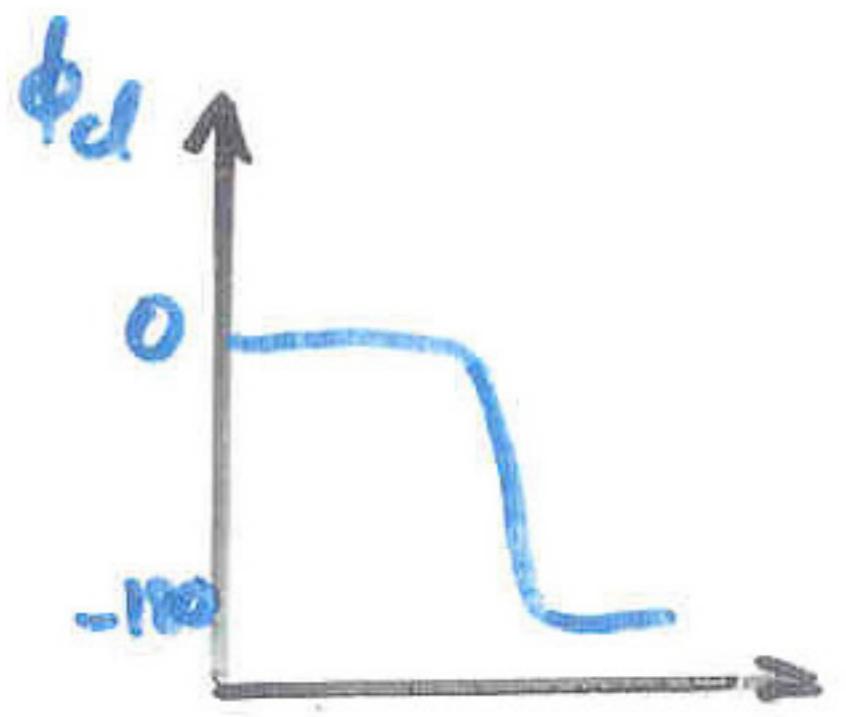
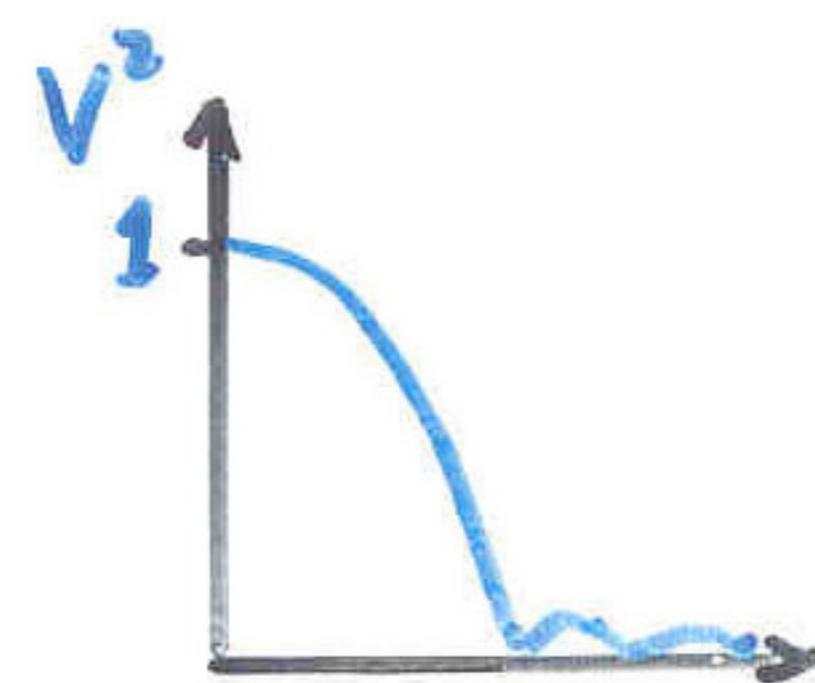


Different arrays for different sources

- Imaging extended structure (assuming bright compact structure to track on): as in radio interferometry, get as wide a variety of baseline lengths as possible



- Imaging a stellar surface: use a bootstrapped array

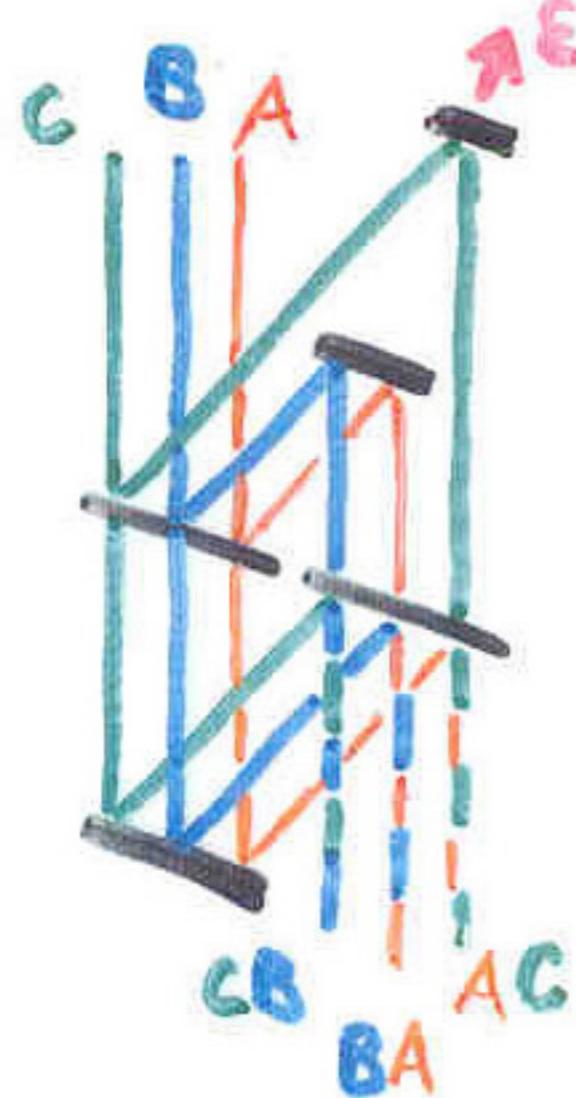


Calibration

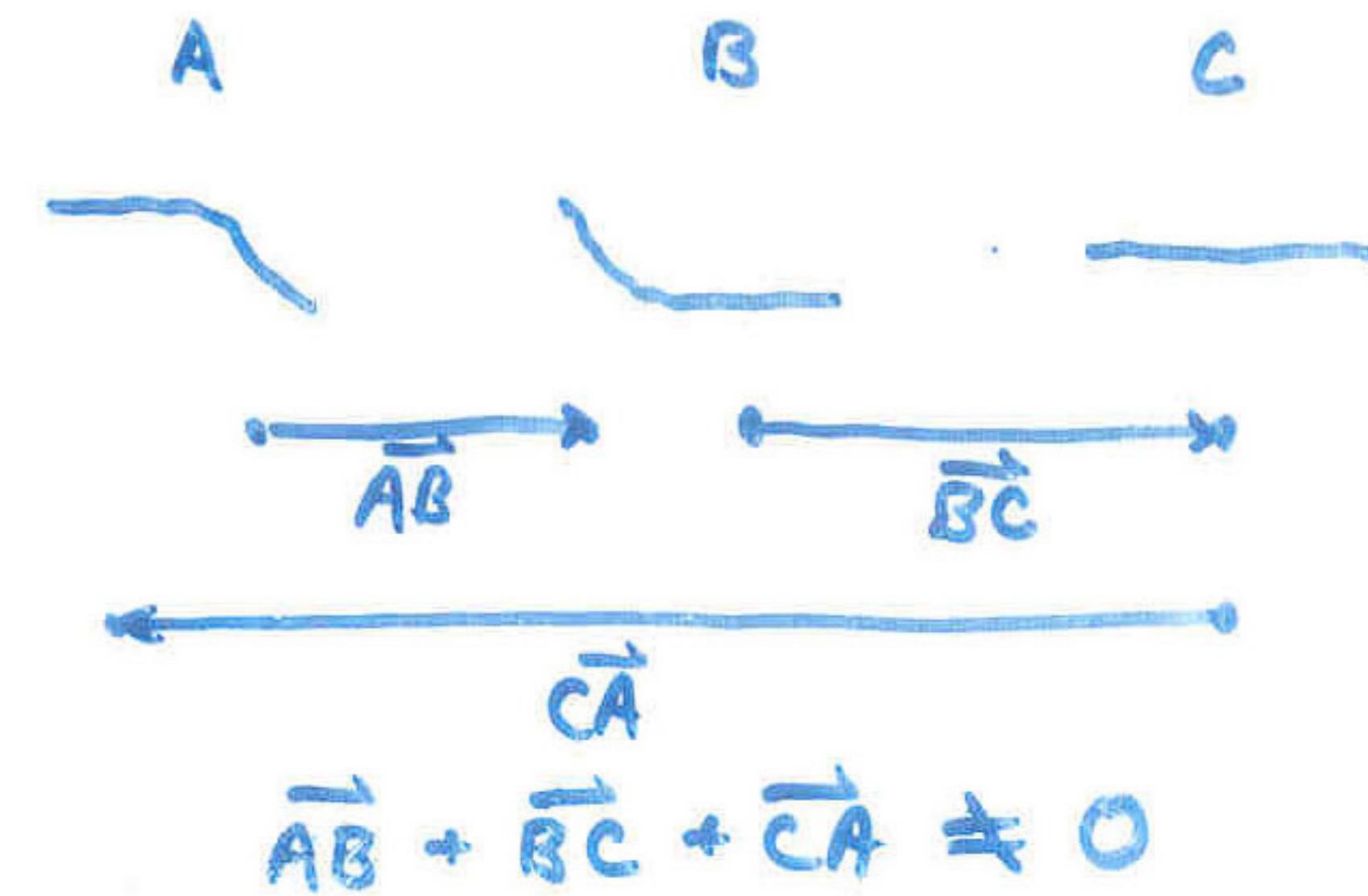
- Concentrate on closure phase
- Use NPOI data (multiple wavelengths) as an example

What can go wrong with closure phase?
It's a direct observable of the source. right?

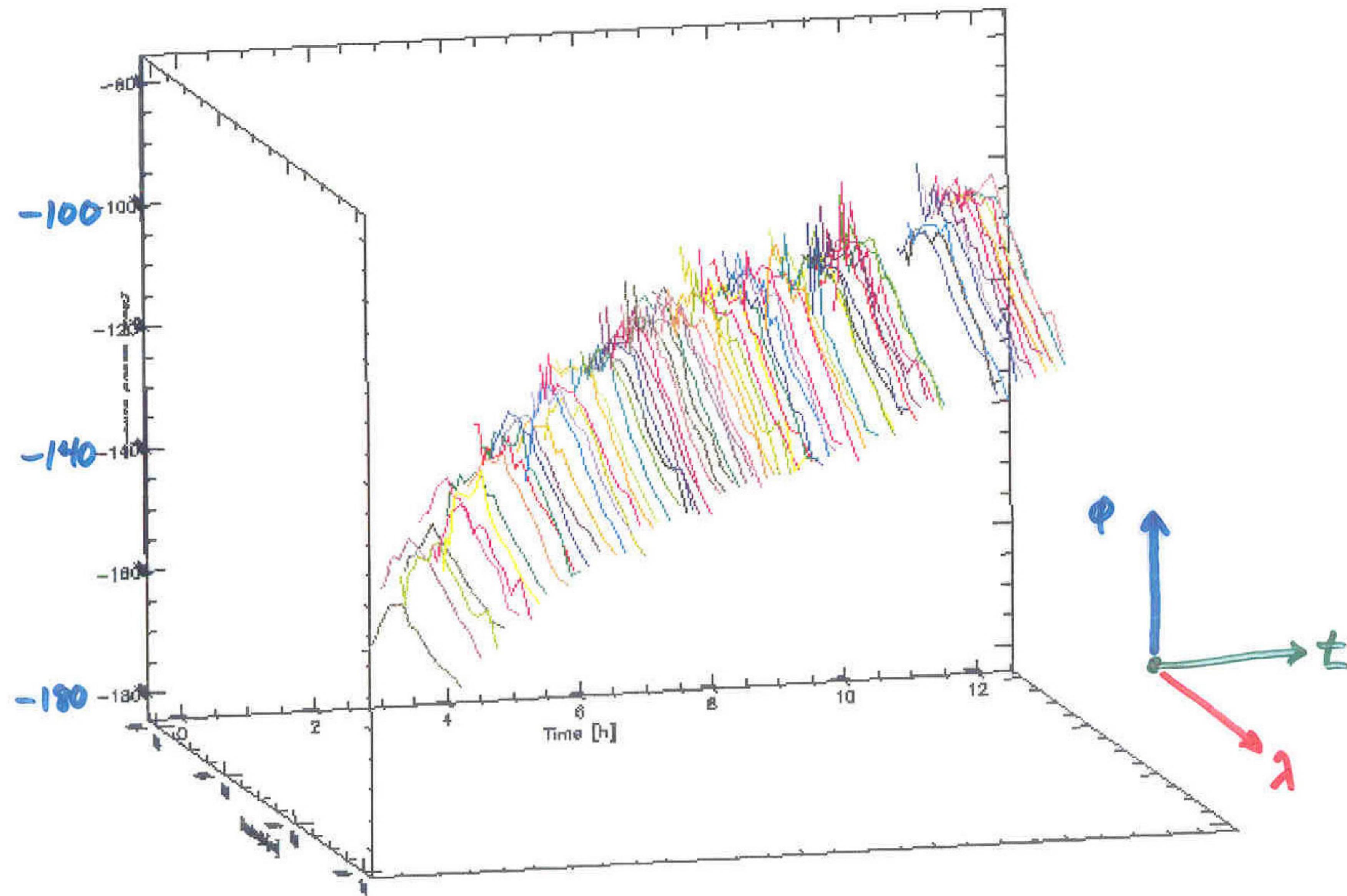
- Air- or glass-path mismatches after pairwise combination
- Path errors in beam combiner
- Nonclosure of apparently closed triangles



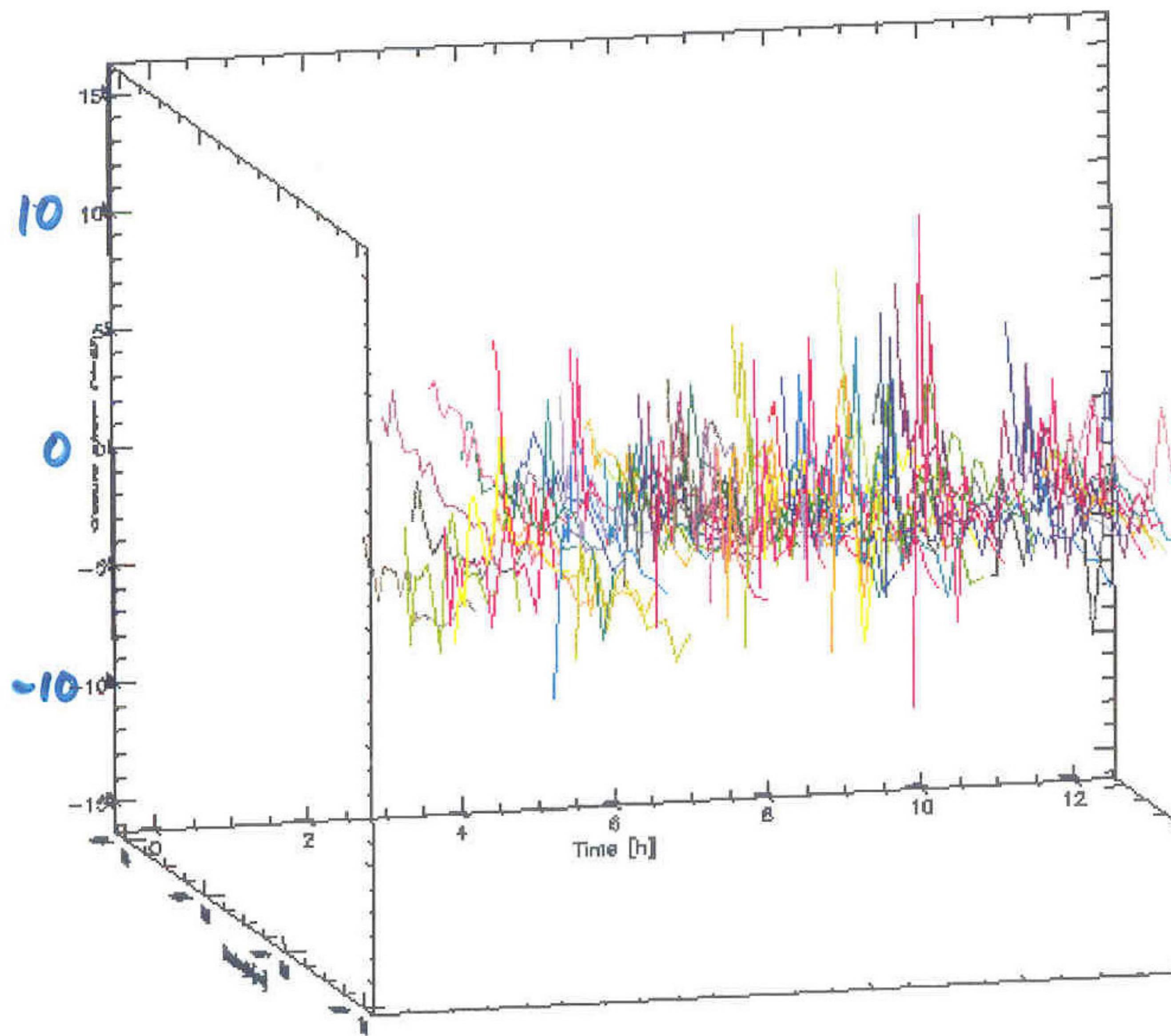
$$\phi_{cl} = \phi_{CB} + \phi_{BA} + \phi_{AC} + \epsilon$$



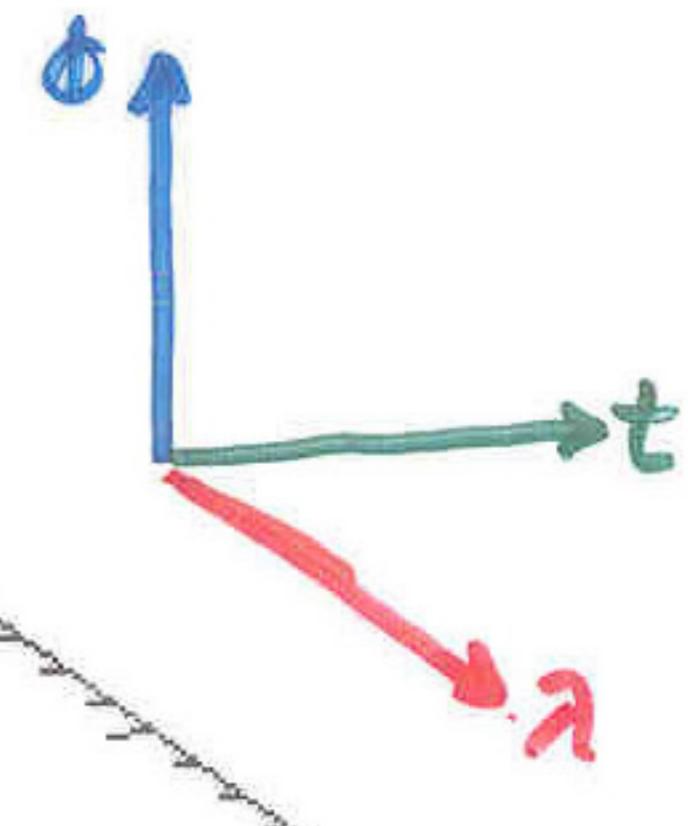
UNCALIBRATED CLOSURE PHASE (unresolved stars)



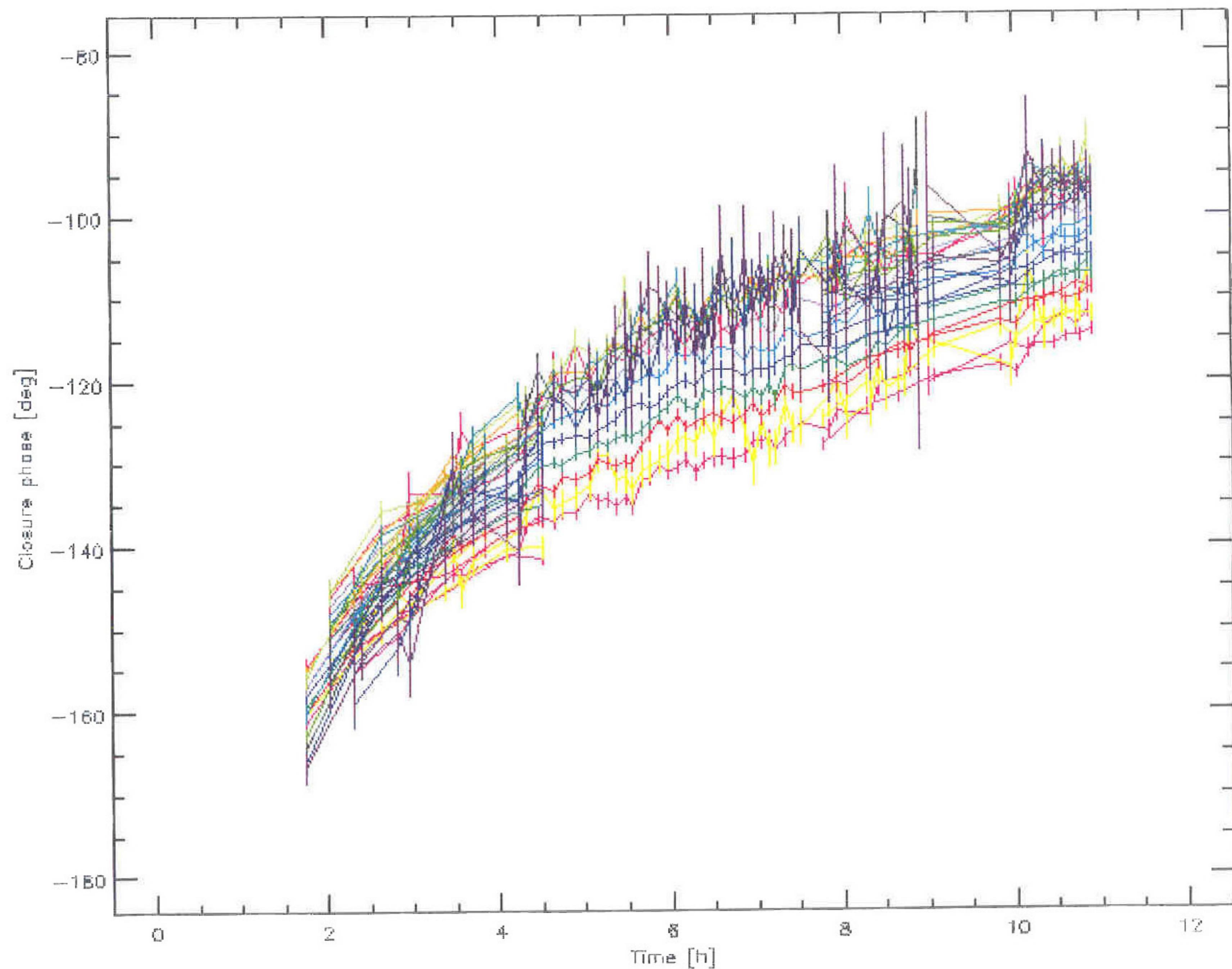
CALIBRATED ϕ_{cl}



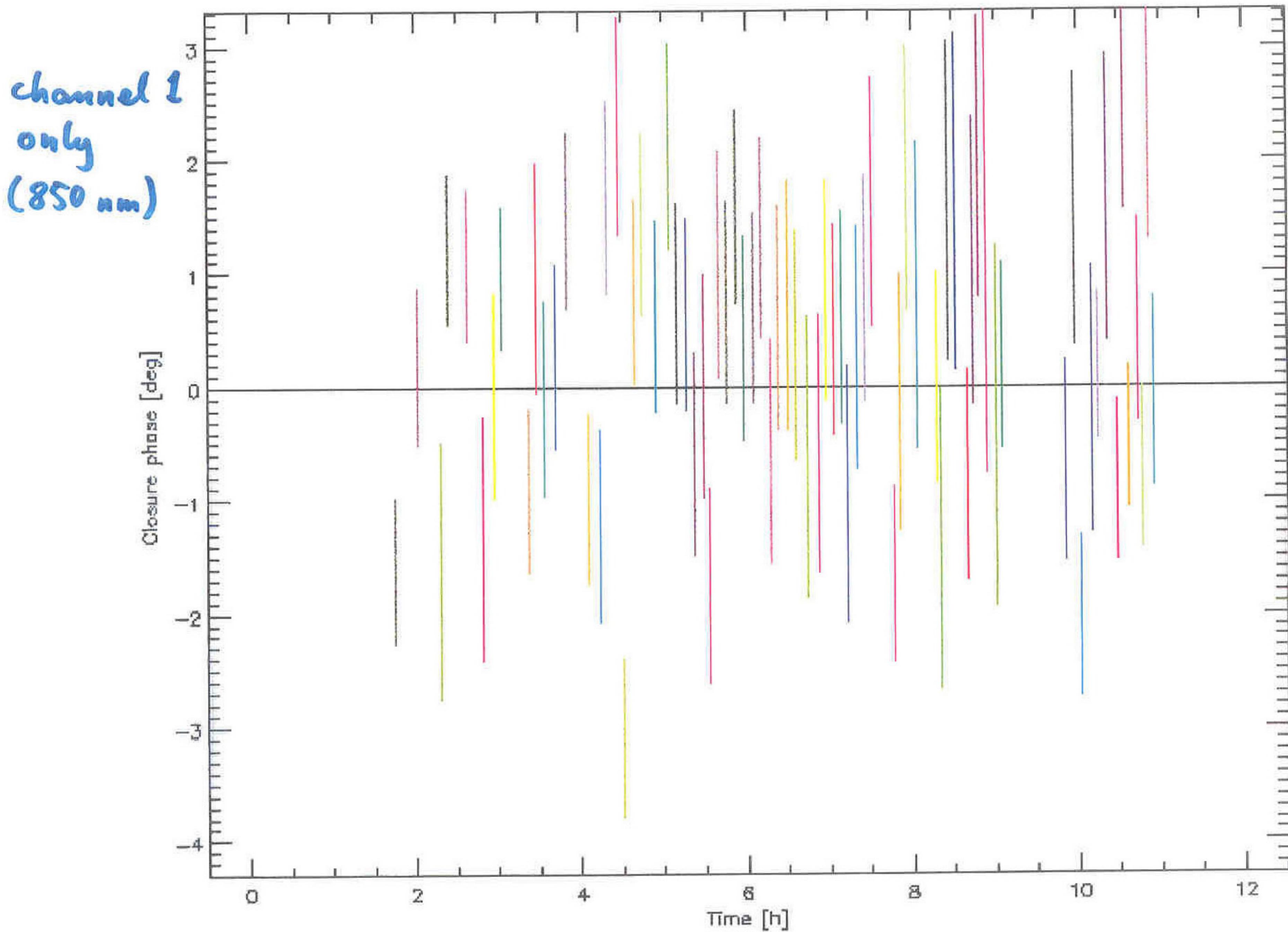
80-min smoothing
channels smoothed
independently



UNCALIBRATED CLOSURE PHASE



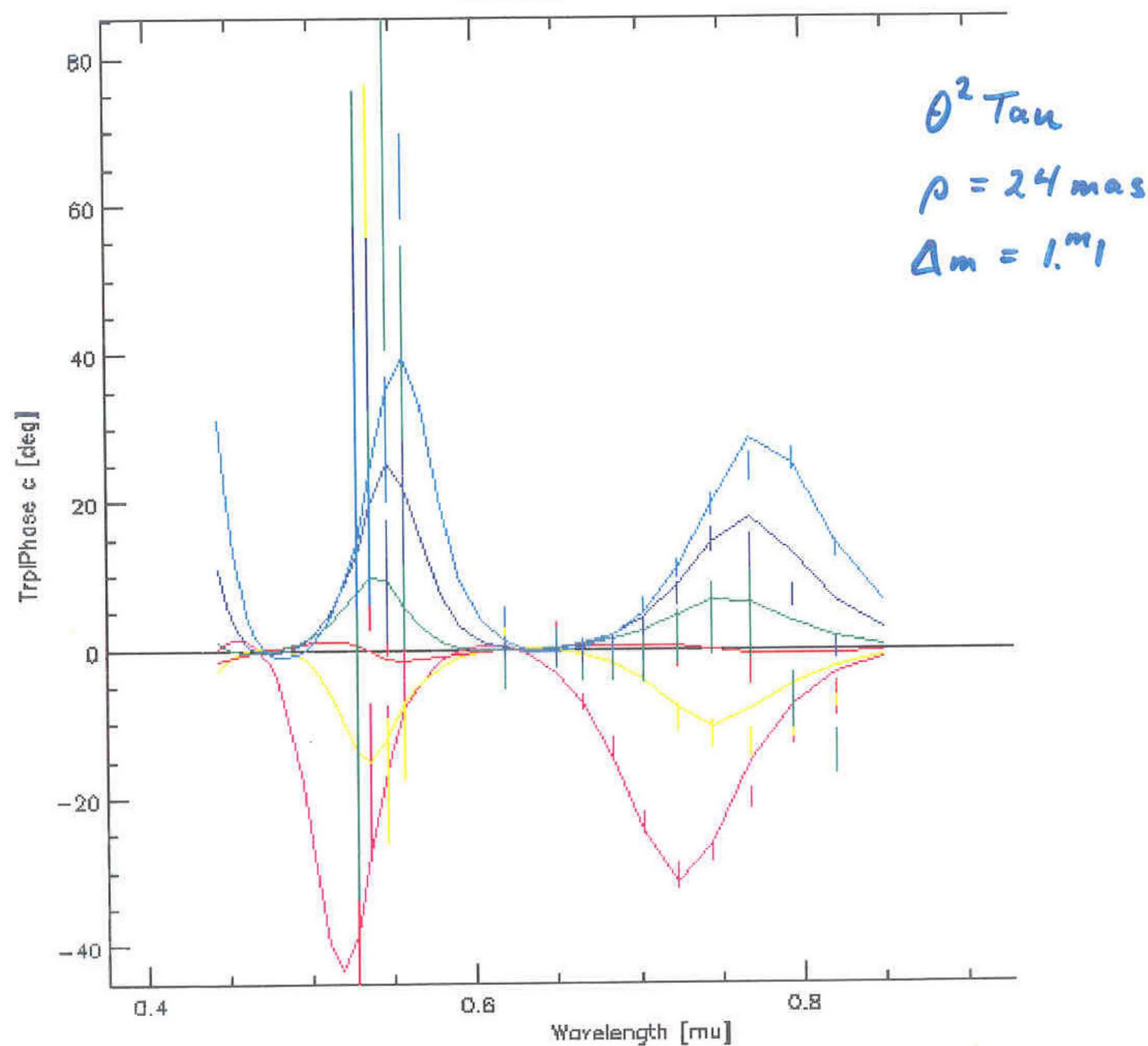
CALIBRATED Closure Phase

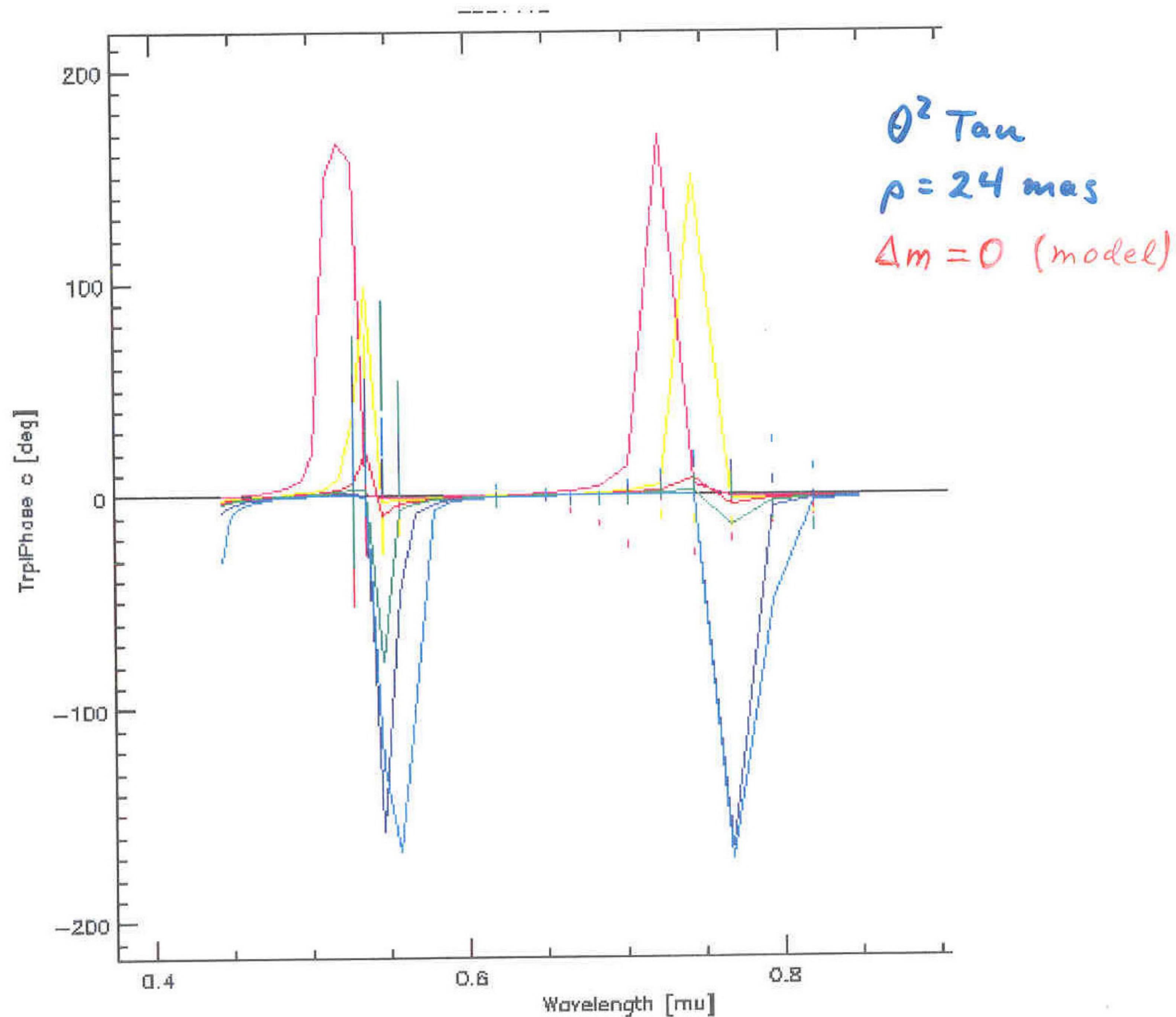


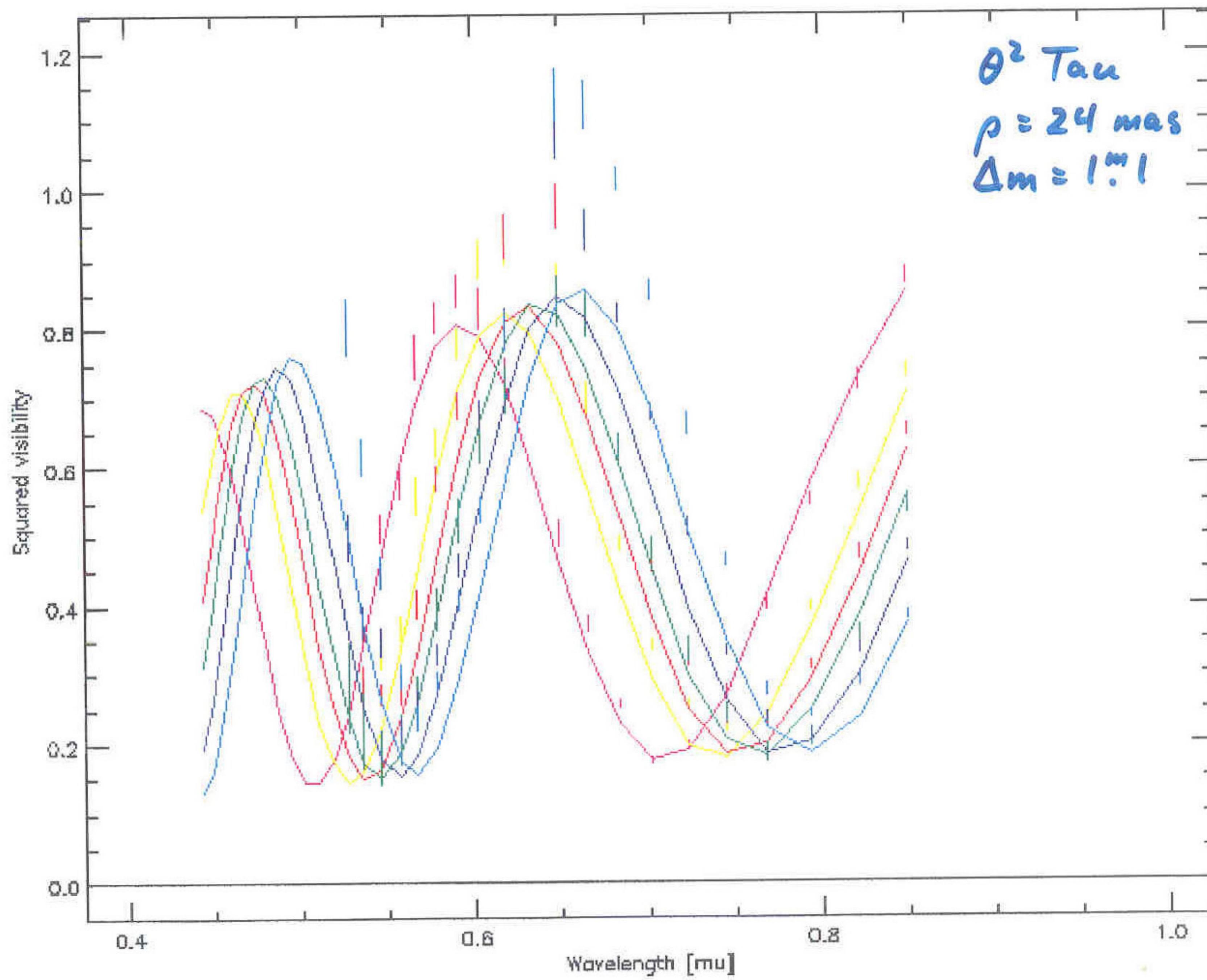
Interpretation: Model fitting

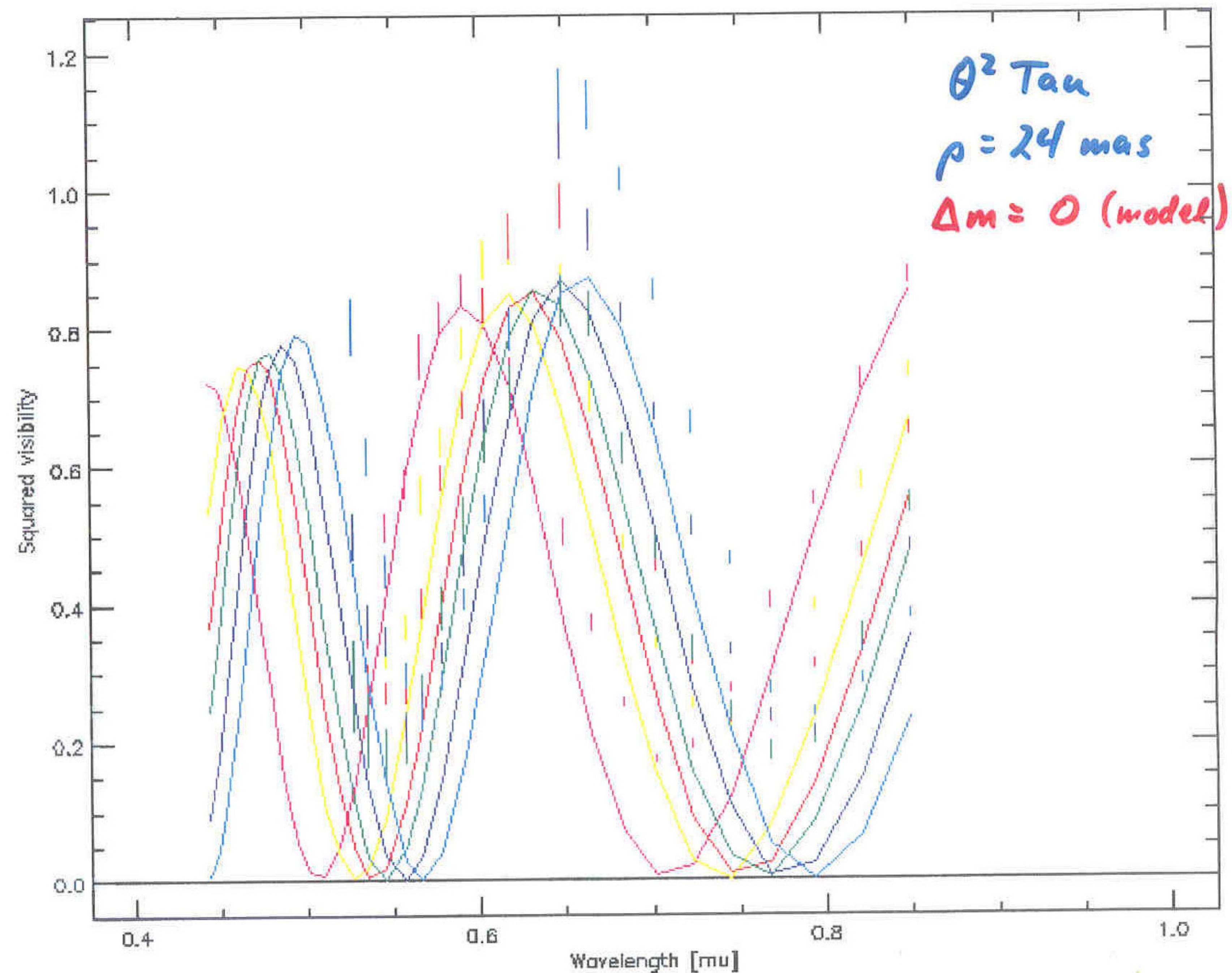
- Technique: minimize
 $\left| \phi_{\text{model}}^{(3)}(\mathbf{u}_1, \mathbf{u}_2) - \phi_{\text{obs}}^{(3)}(\mathbf{u}_1, \mathbf{u}_2) \right|^2$ and $\left| V^2_{\text{model}}(\mathbf{u}_i) - V^2_{\text{obs}}(\mathbf{u}_i) \right|^2$
- Examples: Stellar diameter; Limb-darkened diameter;
Binary star
- Advantage: Small number of free parameters
- Disadvantage: Hard to handle complex source

BSC1412

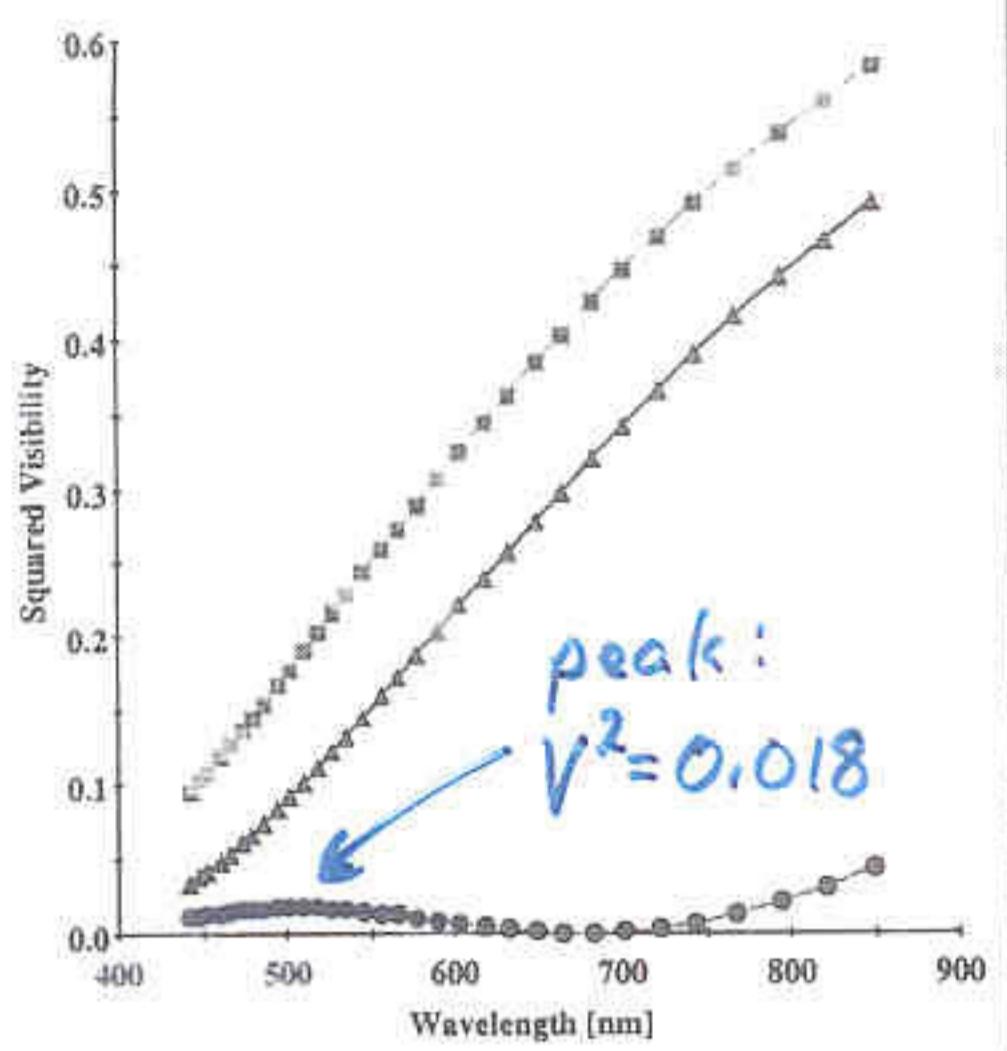




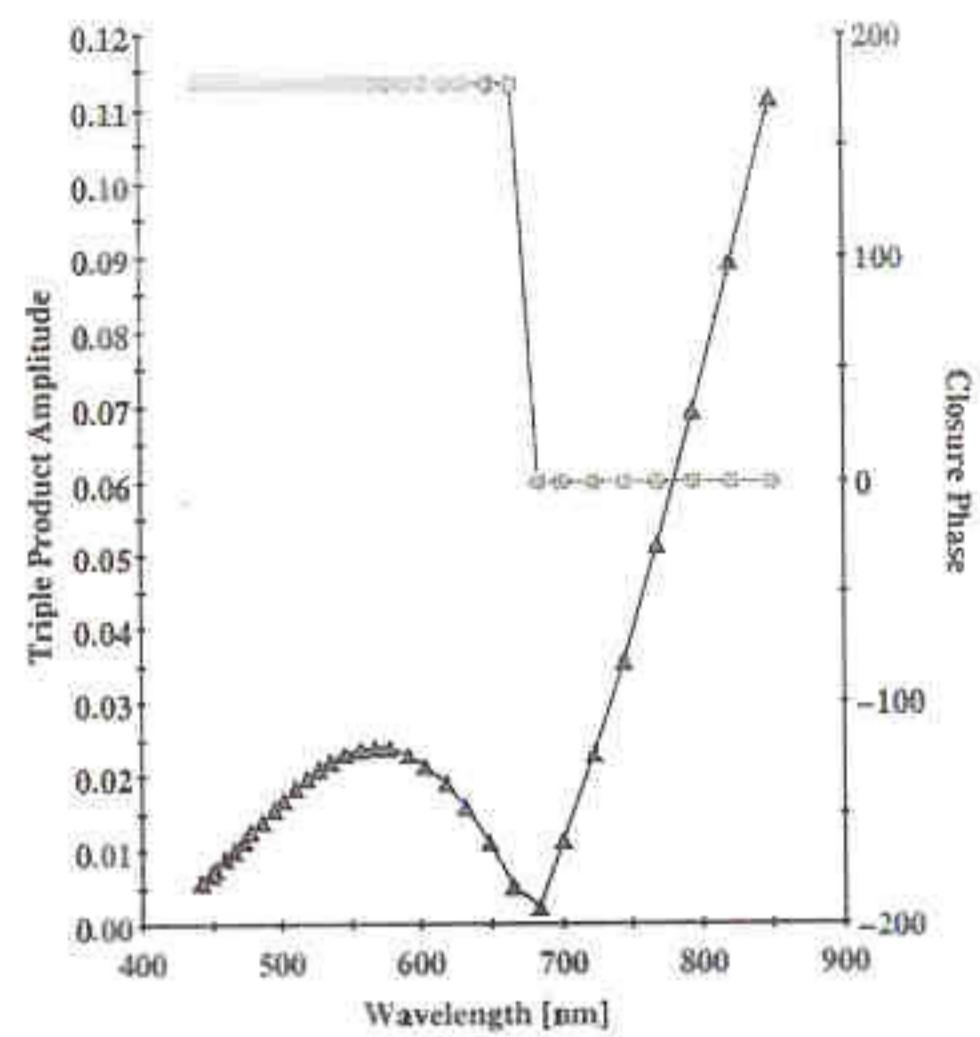




Squared Visibility



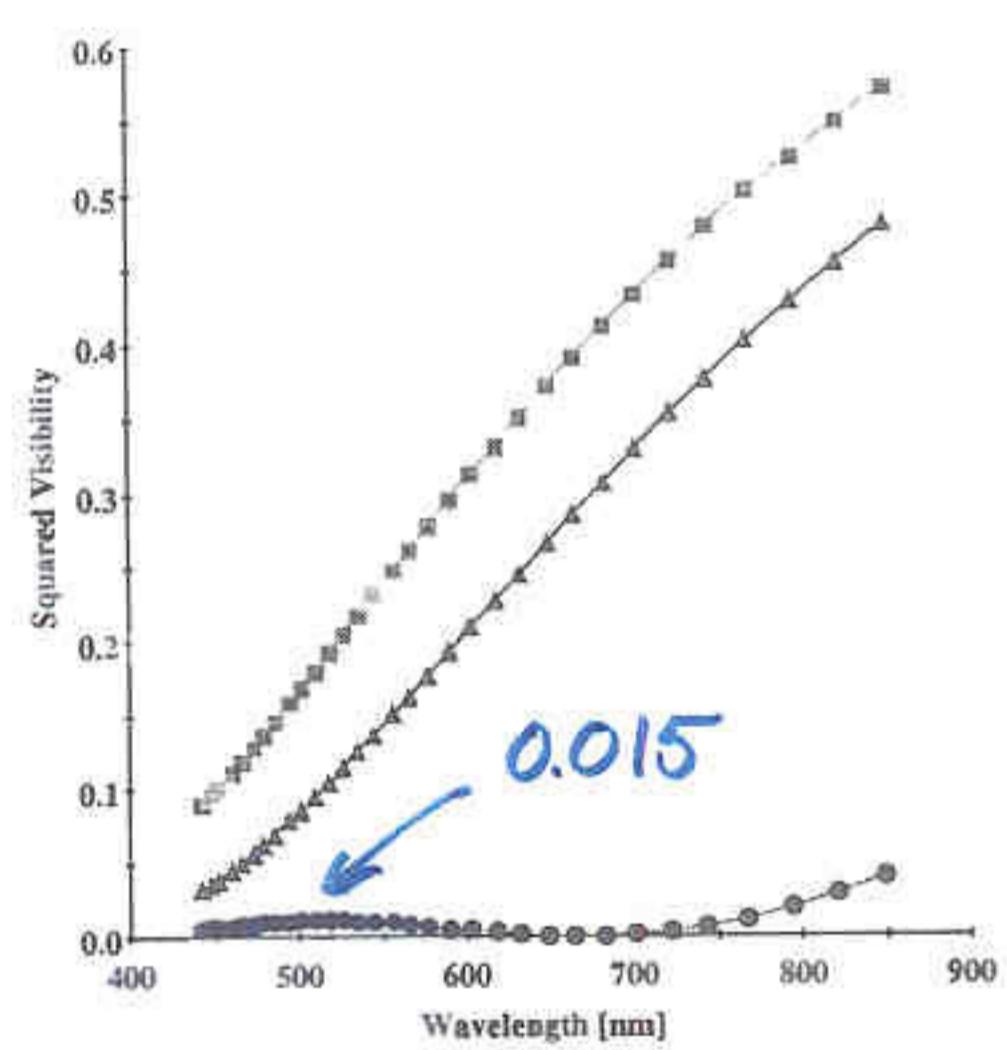
Triple Product and Closure Phase



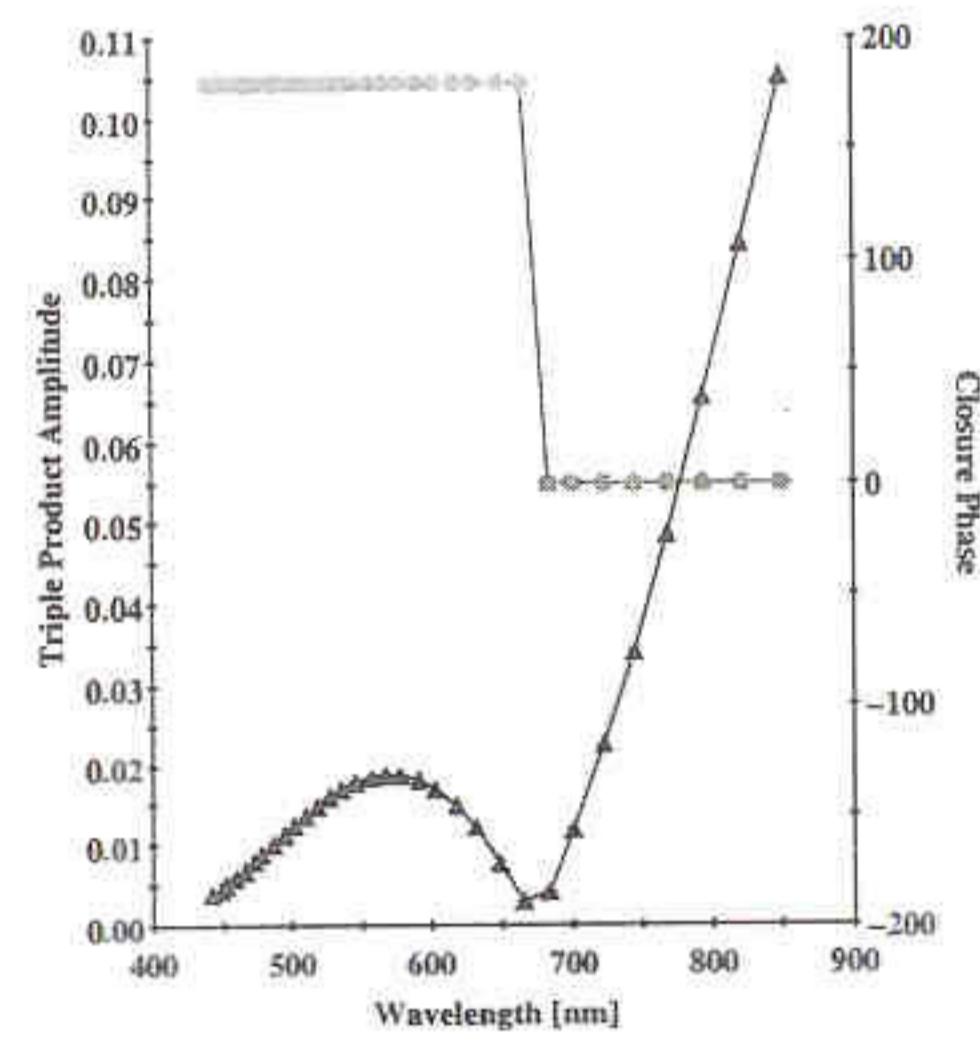
β Cnc
simulation

UNIFORM
DISK
 $\theta_{UD} = 4.85 \text{ mas}$

Squared Visibility

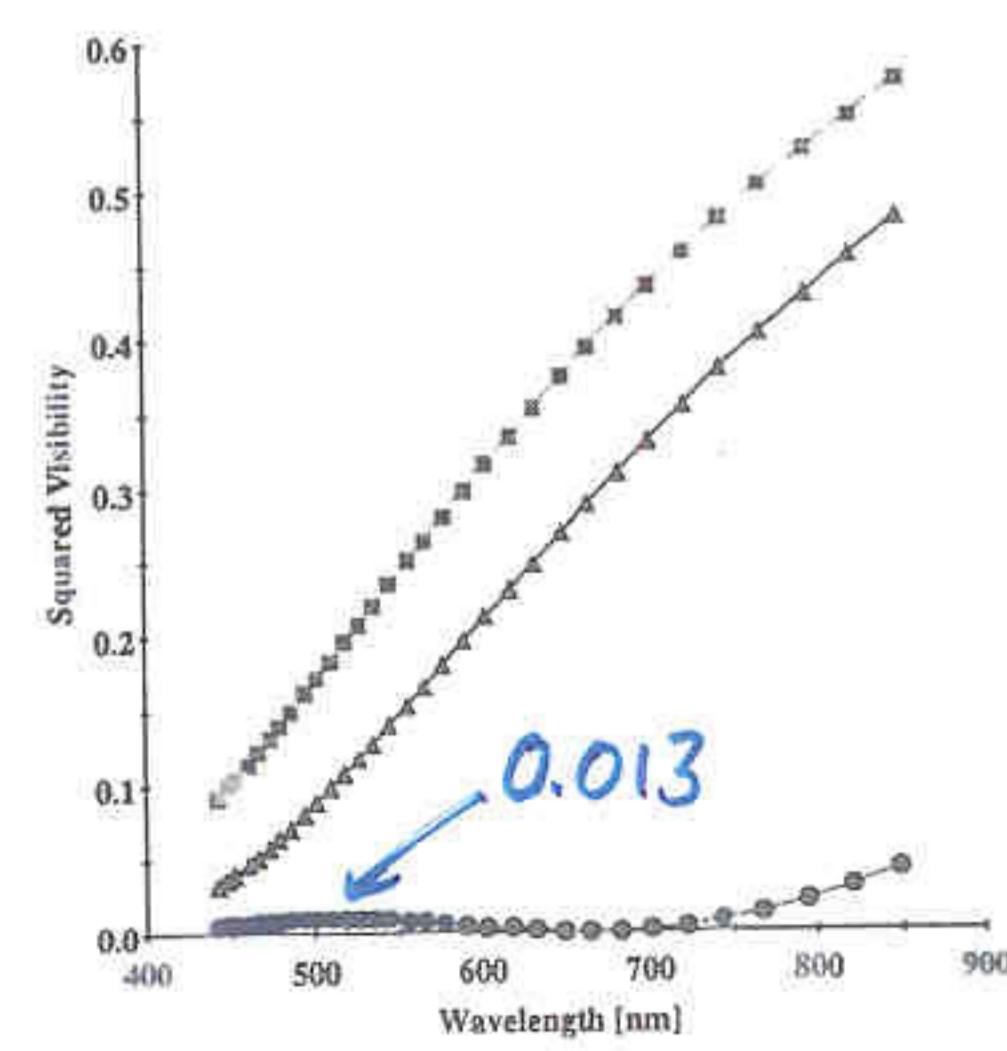


Triple Product and Closure Phase

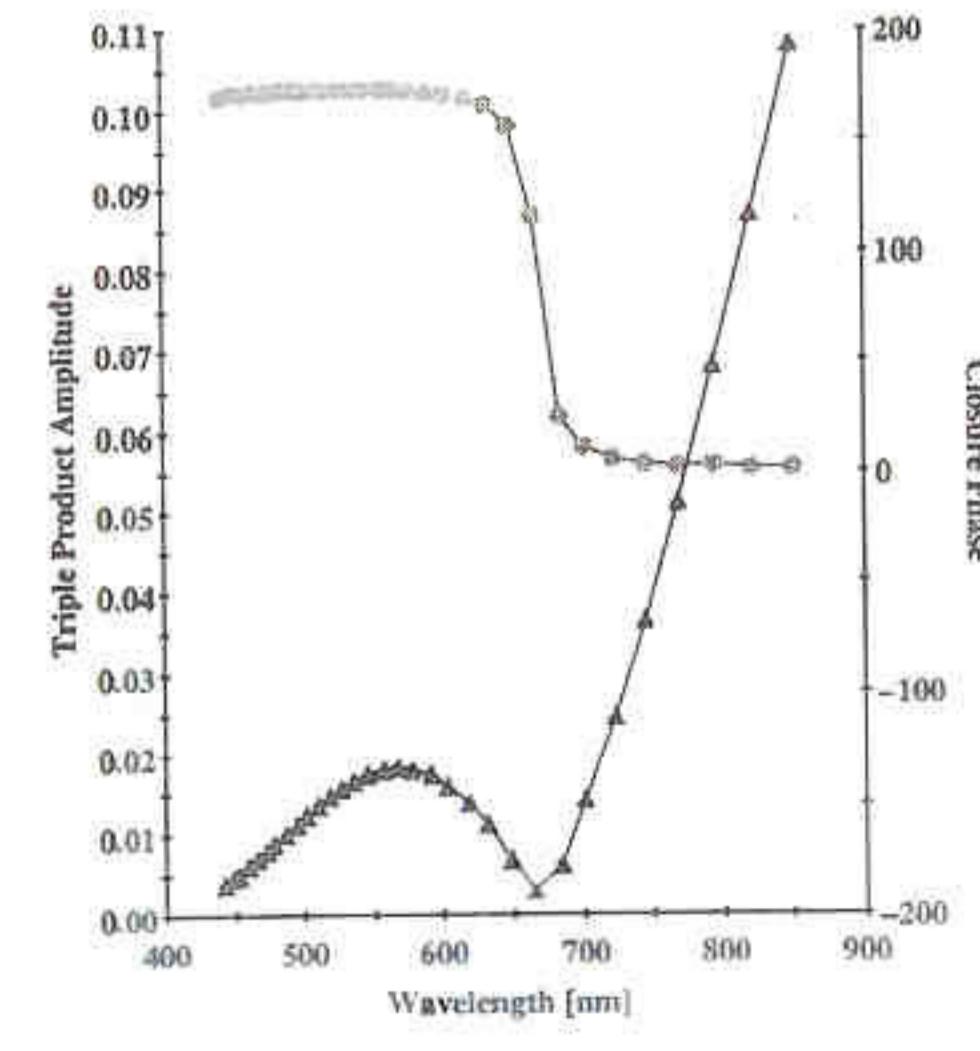


LIMB-DARKENED
DISK
 $\theta_{LD} = 5.20 \text{ mas}$

Squared Visibility



Triple Product and Closure Phase



LIMB-DARKENED
Disk w/SPOT

Interpretation: Imaging

- Technique: $FT^{-1}\{V(\mathbf{u}) \exp[-i\phi_{bl}(\mathbf{u})]\}$
- Examples: Circumstellar material; Stellar surface structure
- Advantage: Not restricted to preconceptions
- Disadvantages: Need to create baseline phases $\phi_{bl}(\mathbf{u})$;
Need to deconvolve point spread function

Turning $\{V^2(\mathbf{u}_i), \phi^{(3)}(\mathbf{u}_i, \mathbf{u}_j)\}$ data

into $\{V(\mathbf{u}_i) \exp[-i\phi(\mathbf{u}_i)]\}$ data

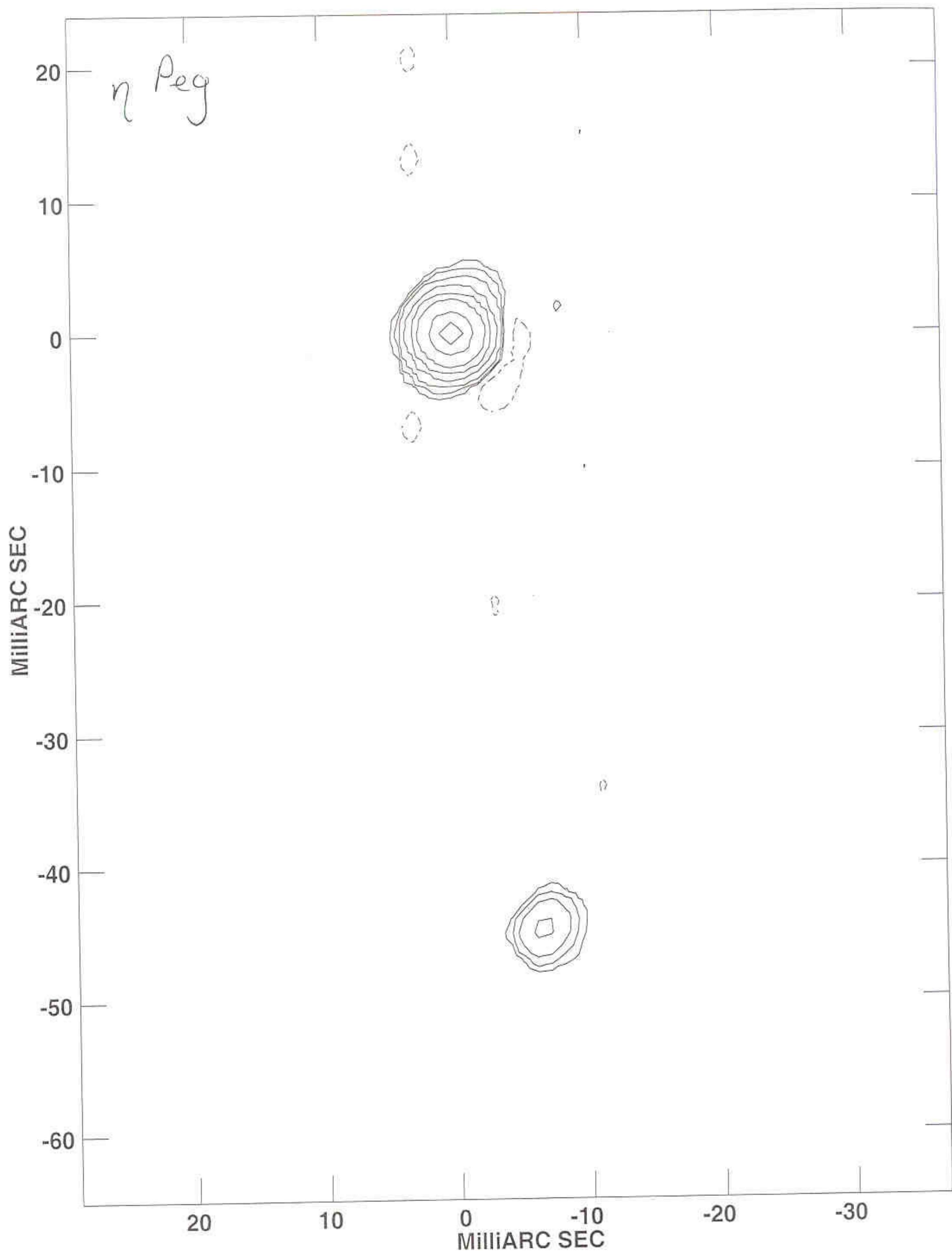
- Assign the closure phase to one of the baseline phases
- Self-calibrate

Current Capabilities and Limitations

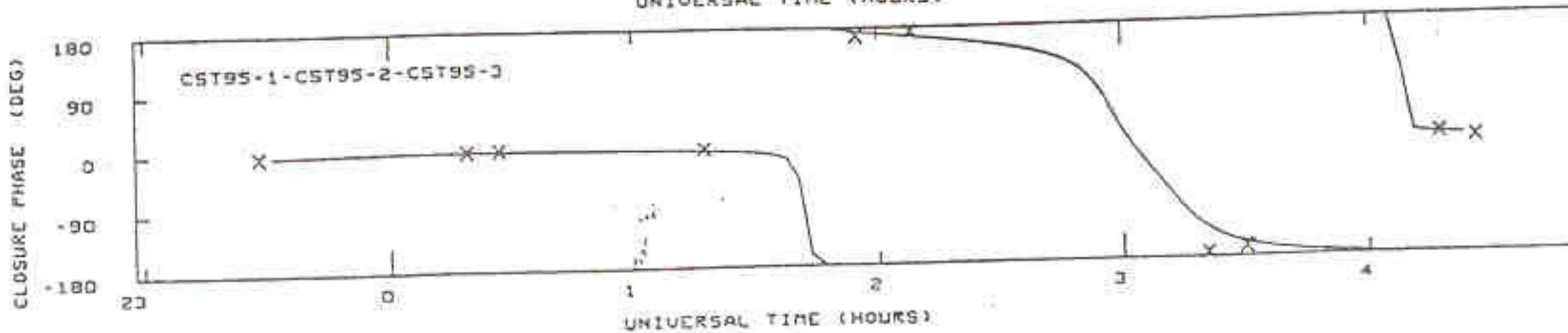
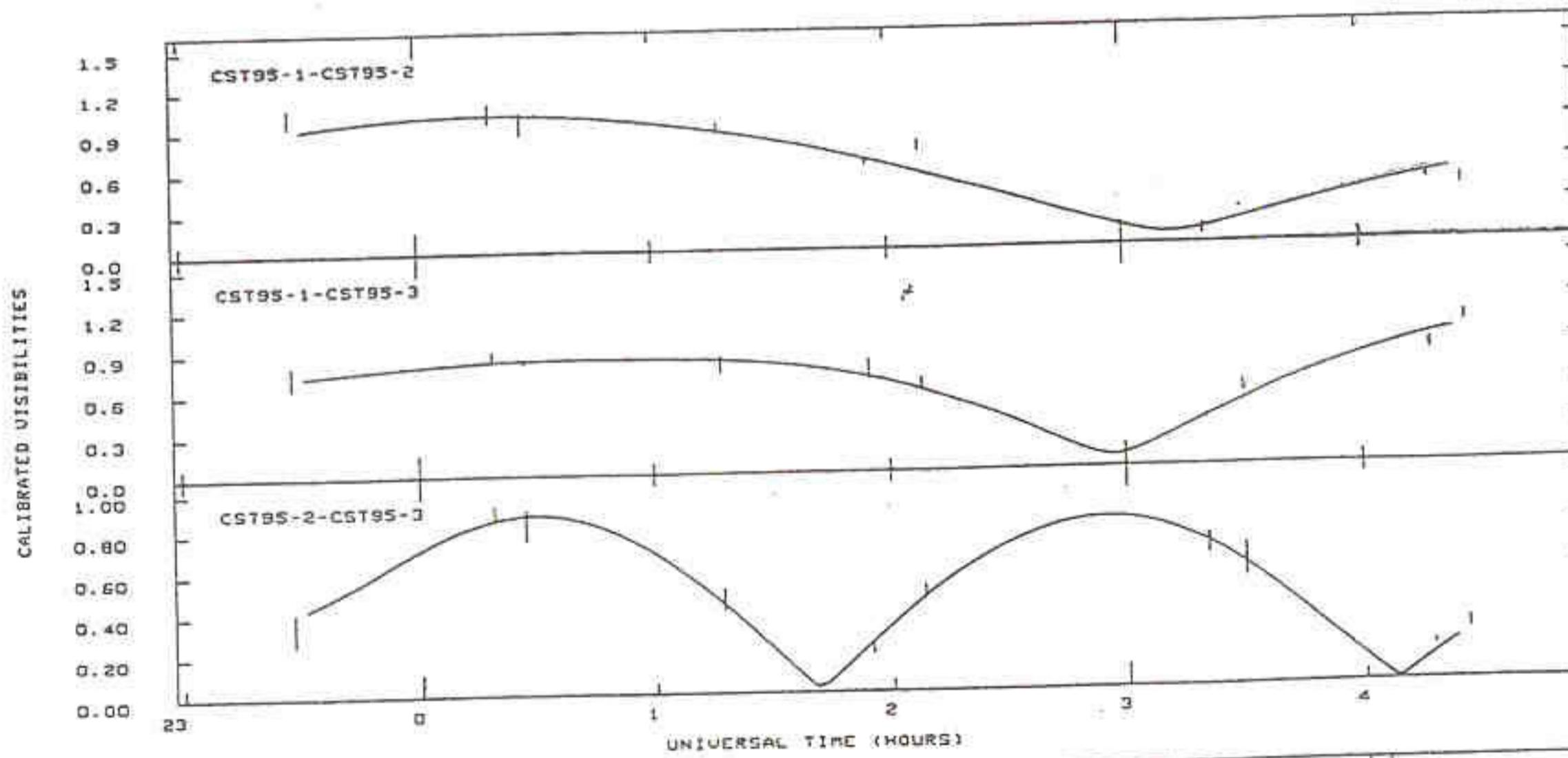
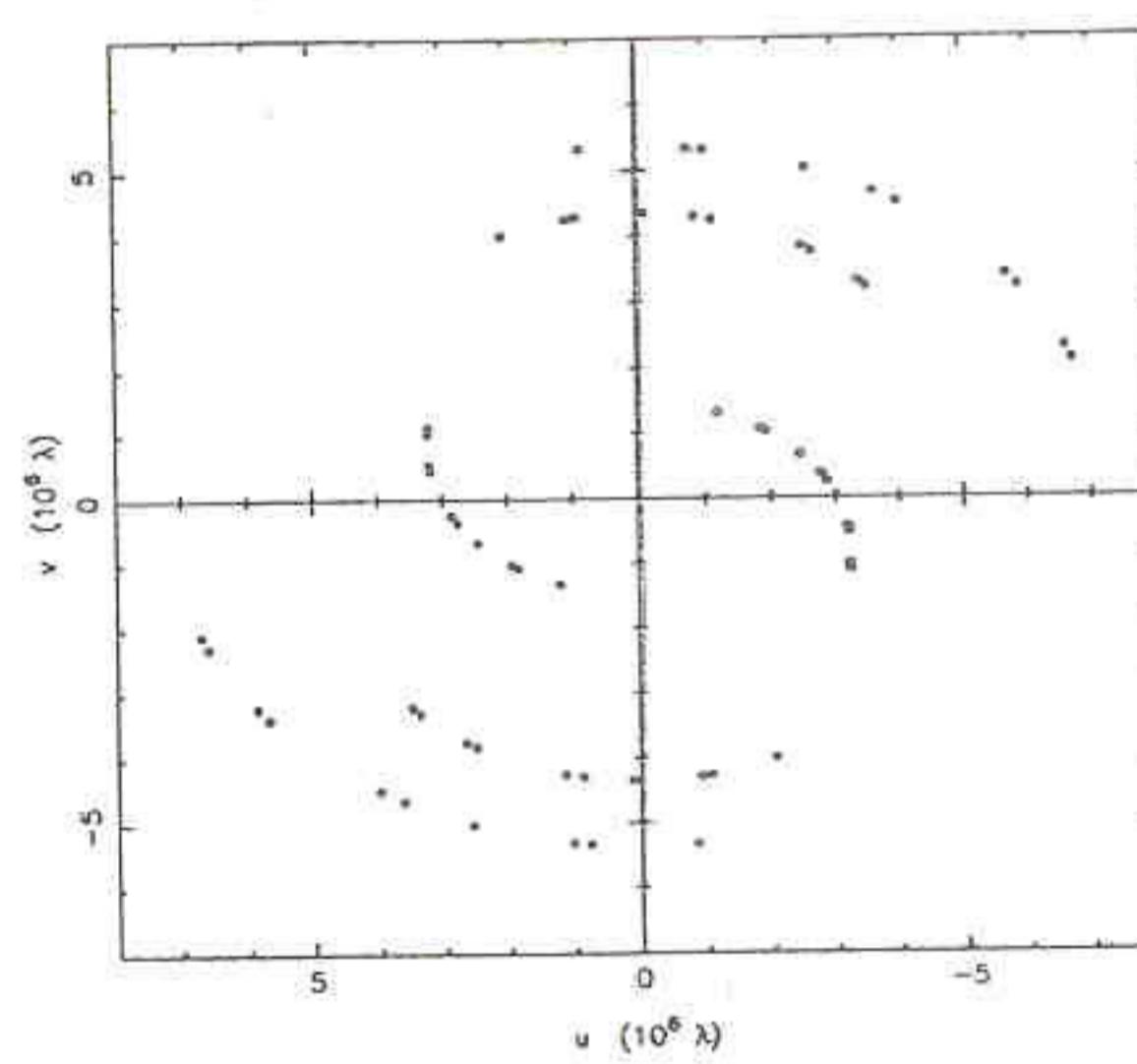
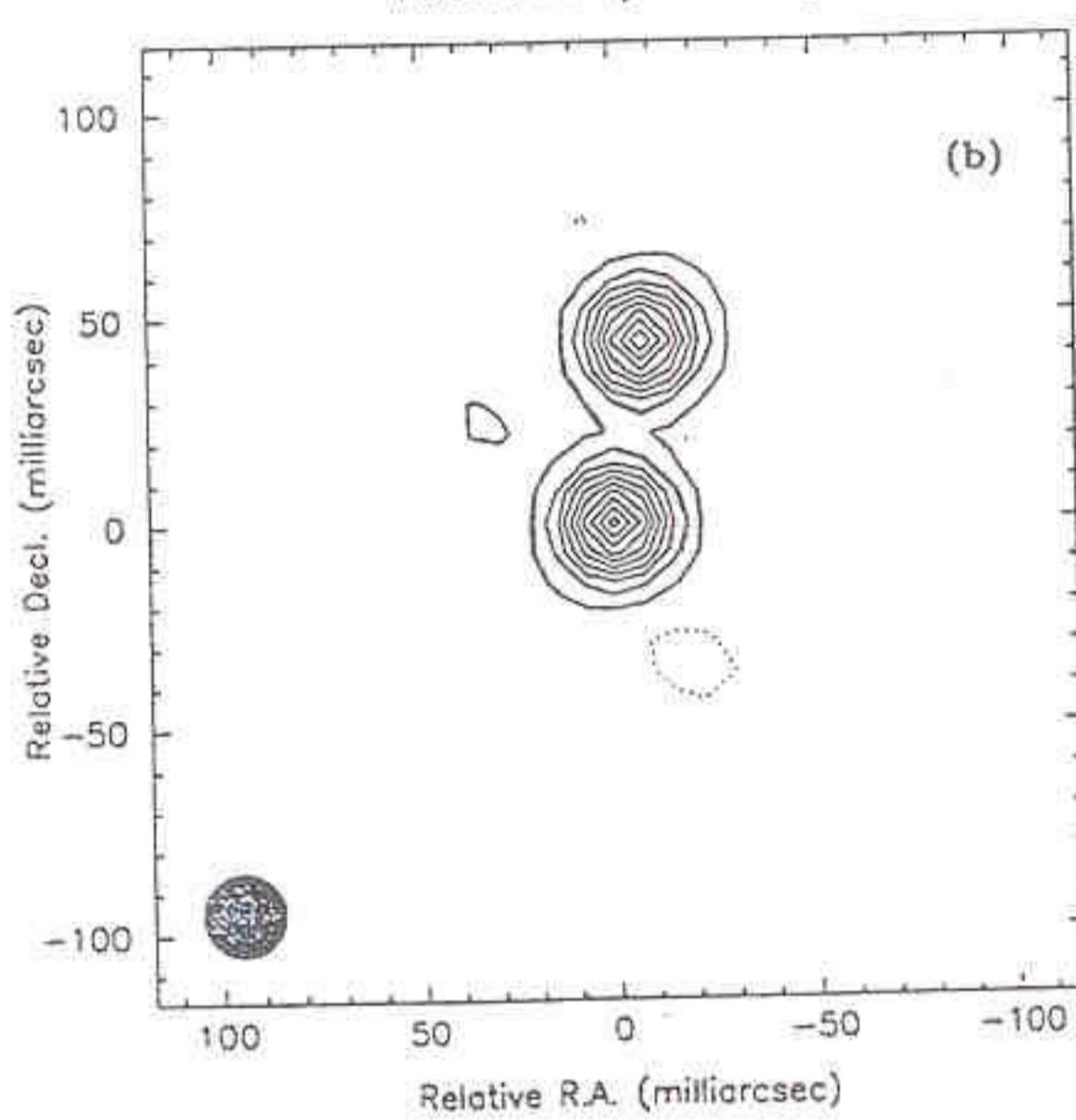
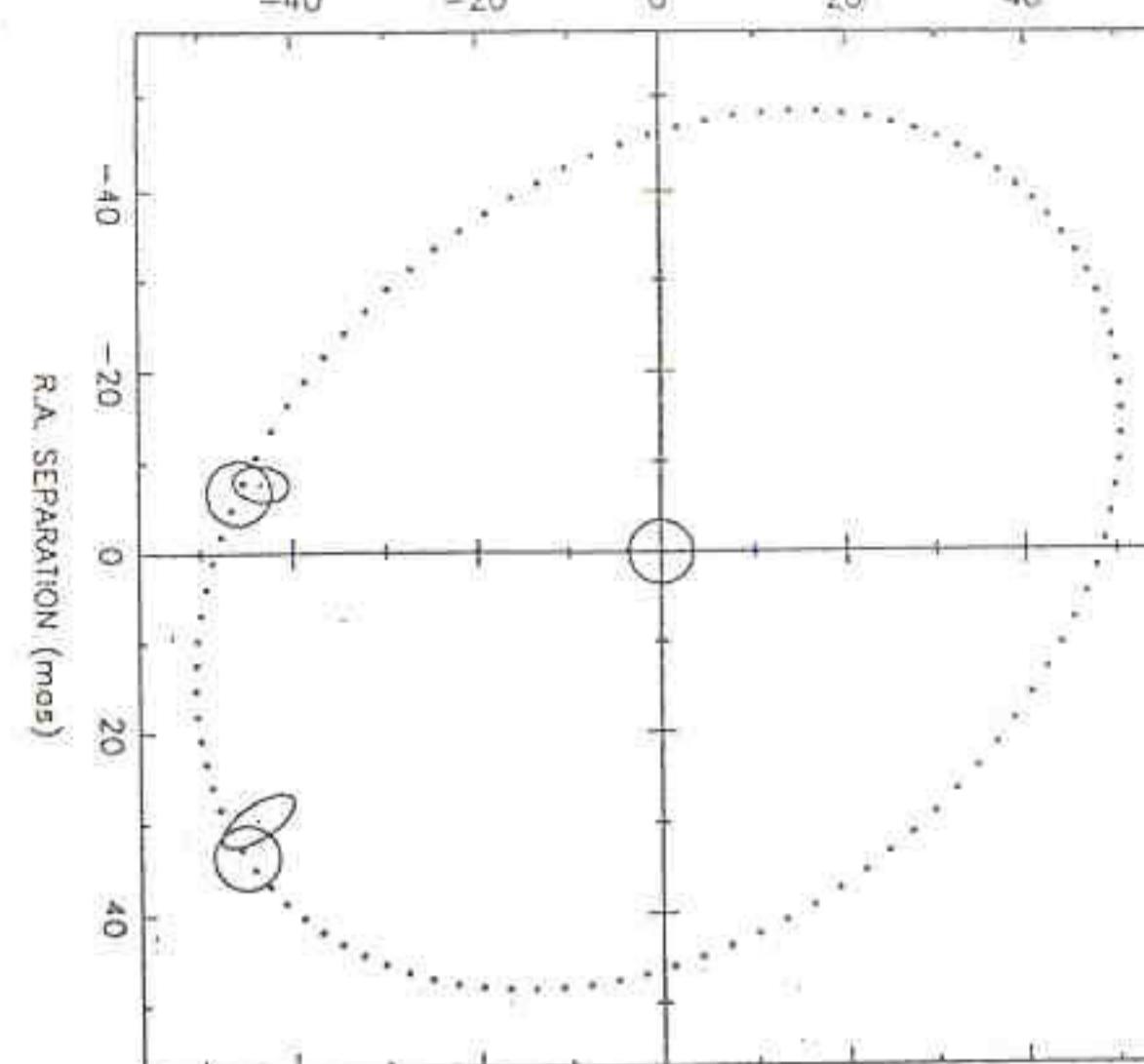
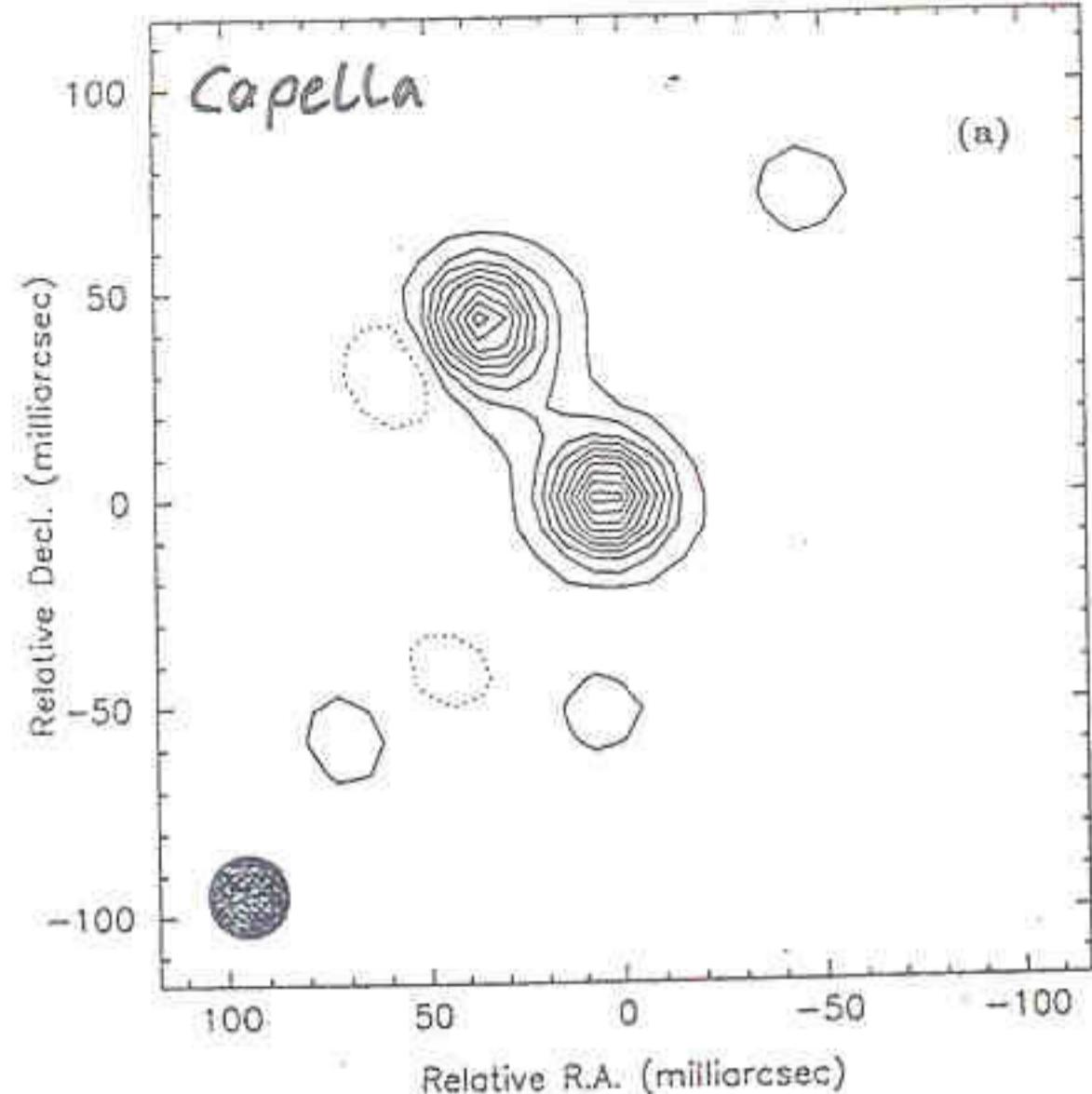
- Limited complexity of sources:
binary stars, diameters, limb darkening
 - Keck masks used 210 baselines, 171 closure phases
 - NPOI currently uses three baselines, one closure phase per spectral channel (96 visibilities and 32 closure phases in total)
- Limited pixels across the stellar disk
- Limited sensitivity: NPOI limited to ~ 5 mag (ultimately expecting a couple magnitudes better)

Future Prospects

- Modeling closure-phase systematics
- Unwrapping baseline phases
- More baselines: simulation of NPOI with 6 elements (15 baselines, 10 closure phases per spectral channel)

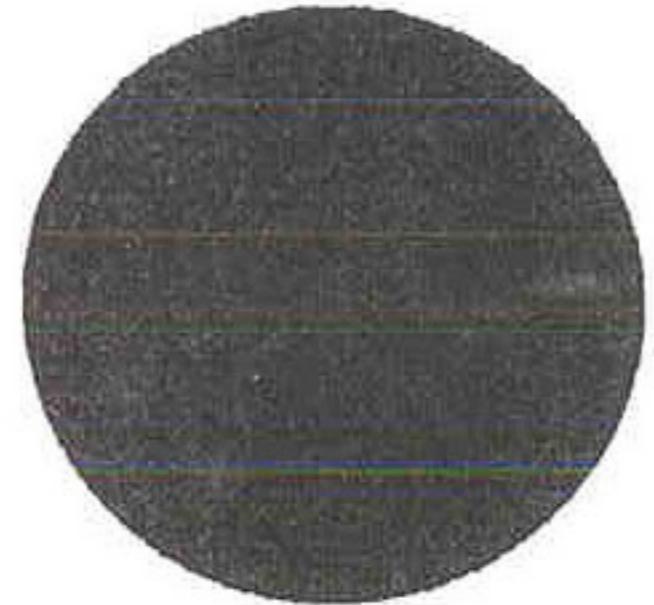


COAST

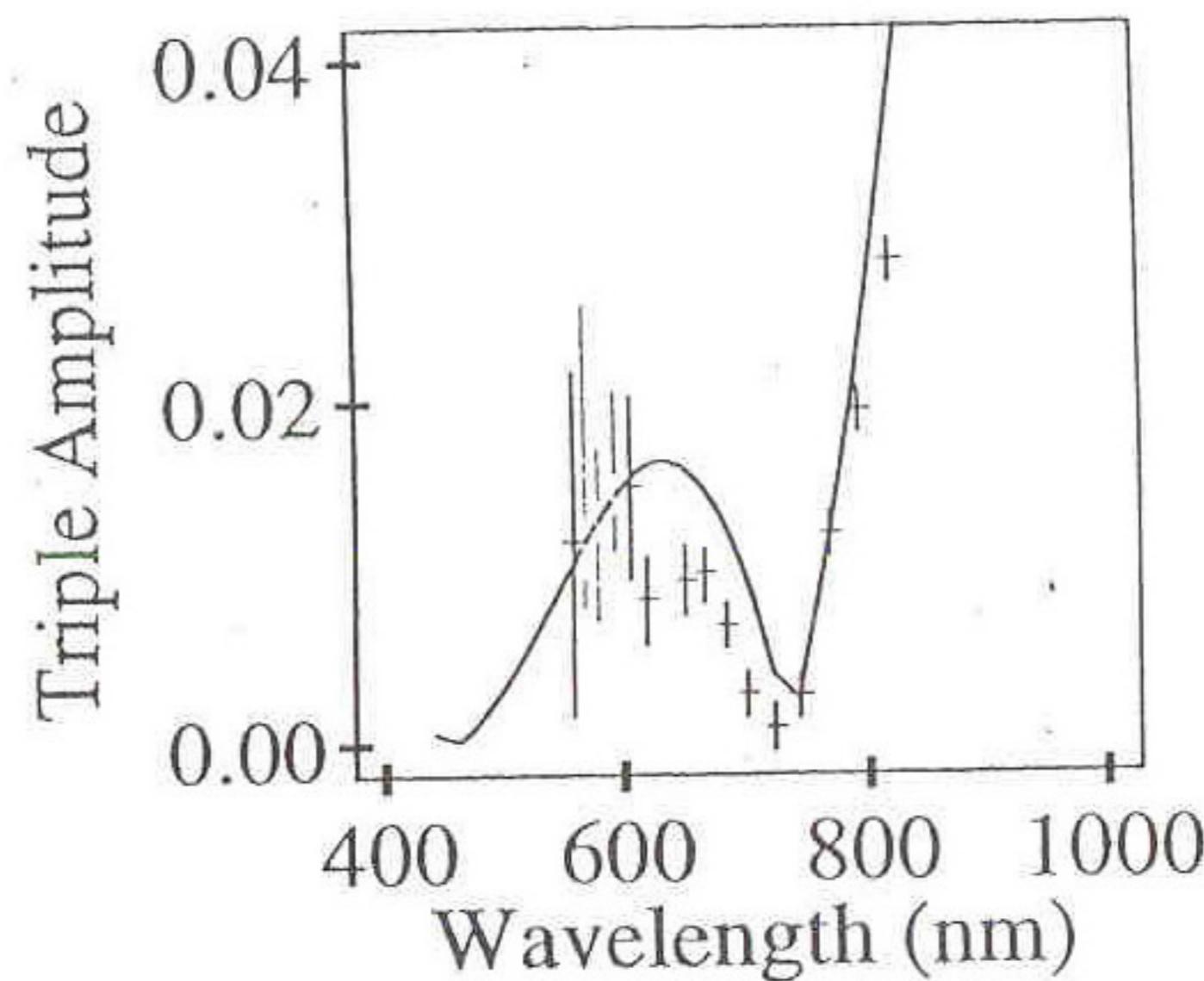


TA 24

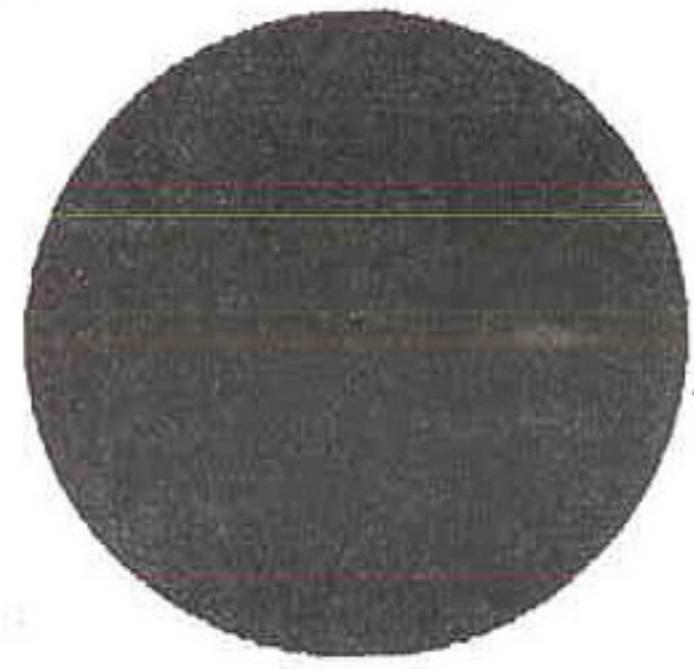
Uniform Disk



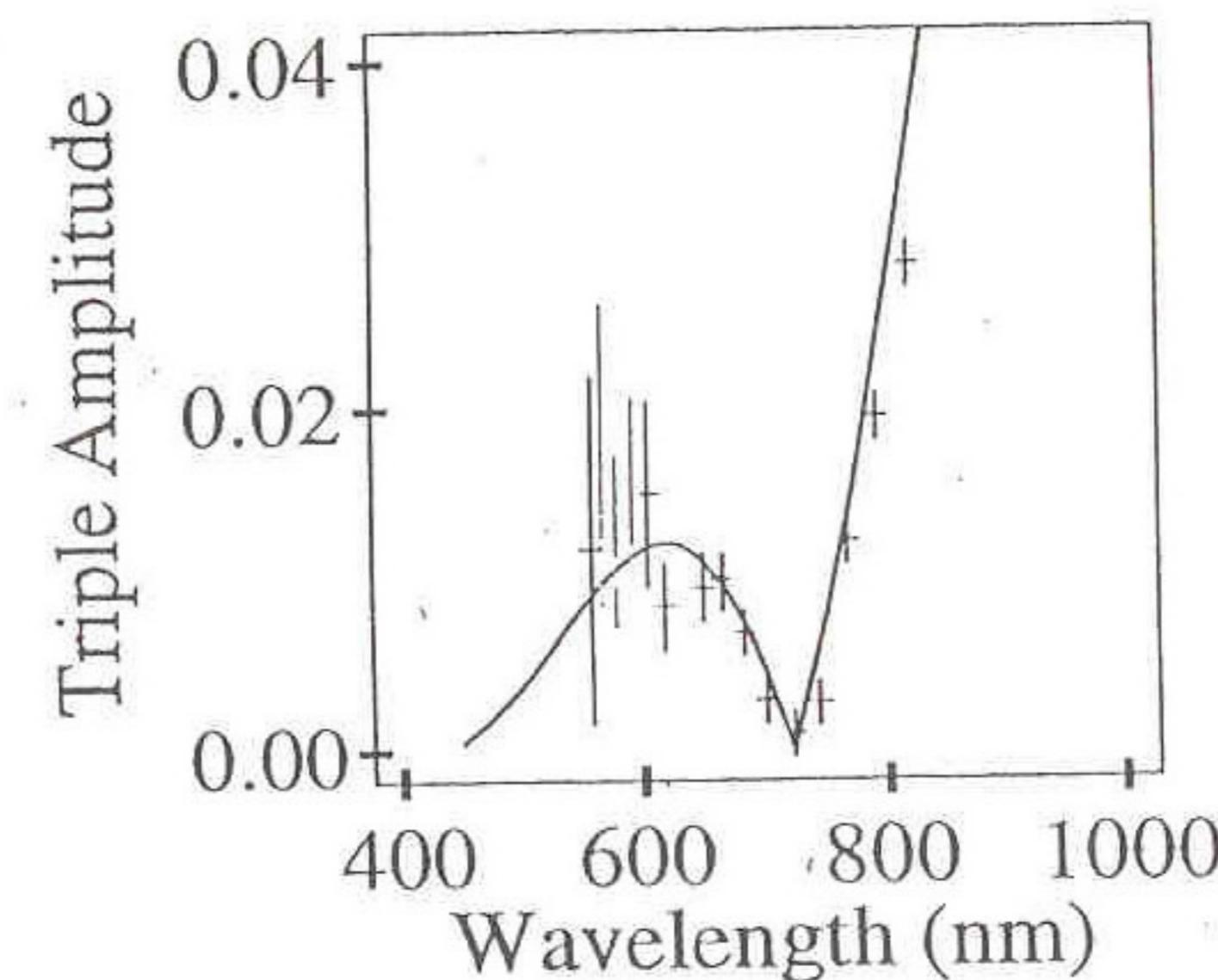
α Cas - Dec 18, 1996.



Limb-Darkened Disk



α Cas - Dec 18, 1996.



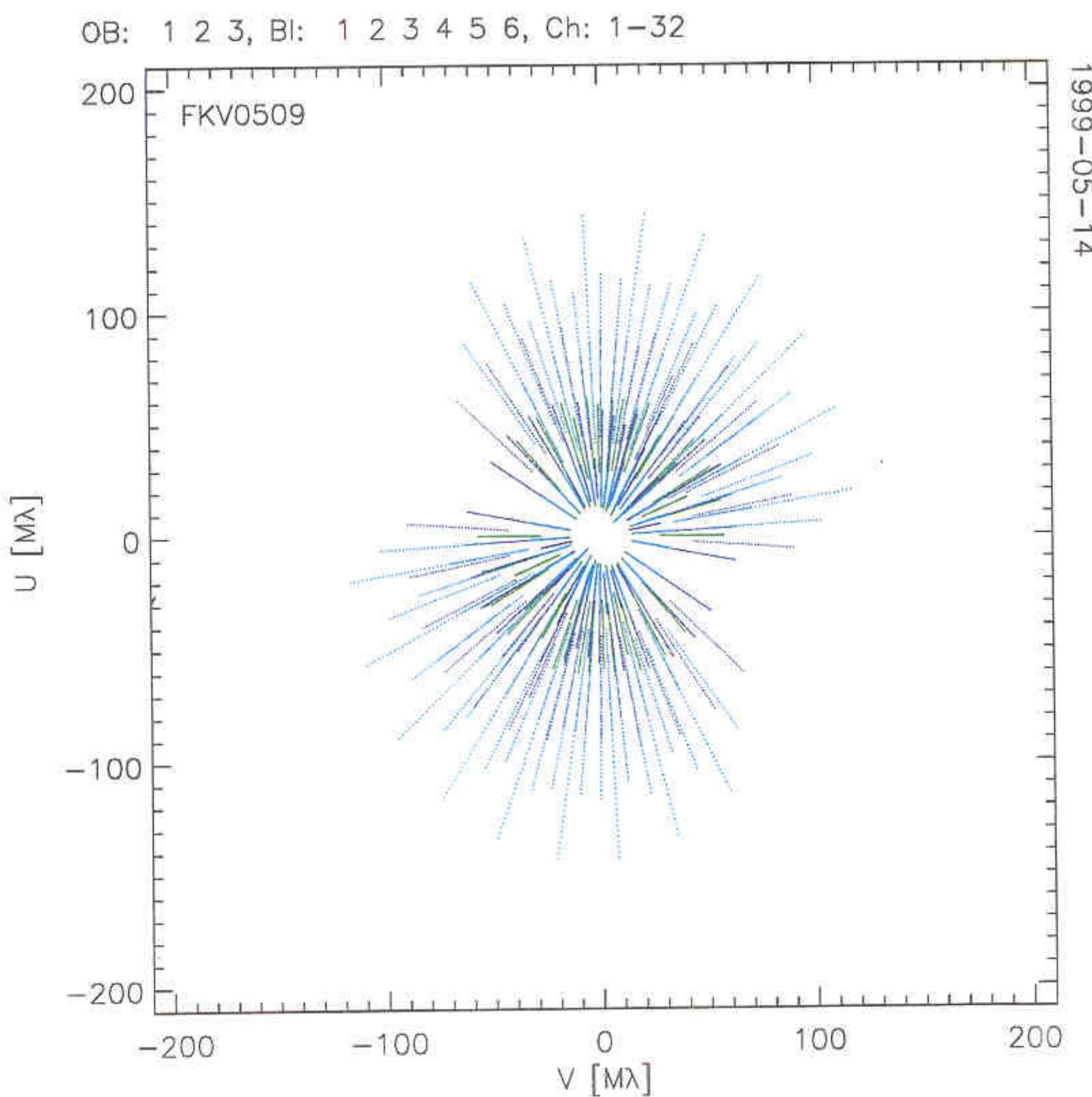
SIMULATION

6 elements \Rightarrow 15 baselines
10 closure triangles

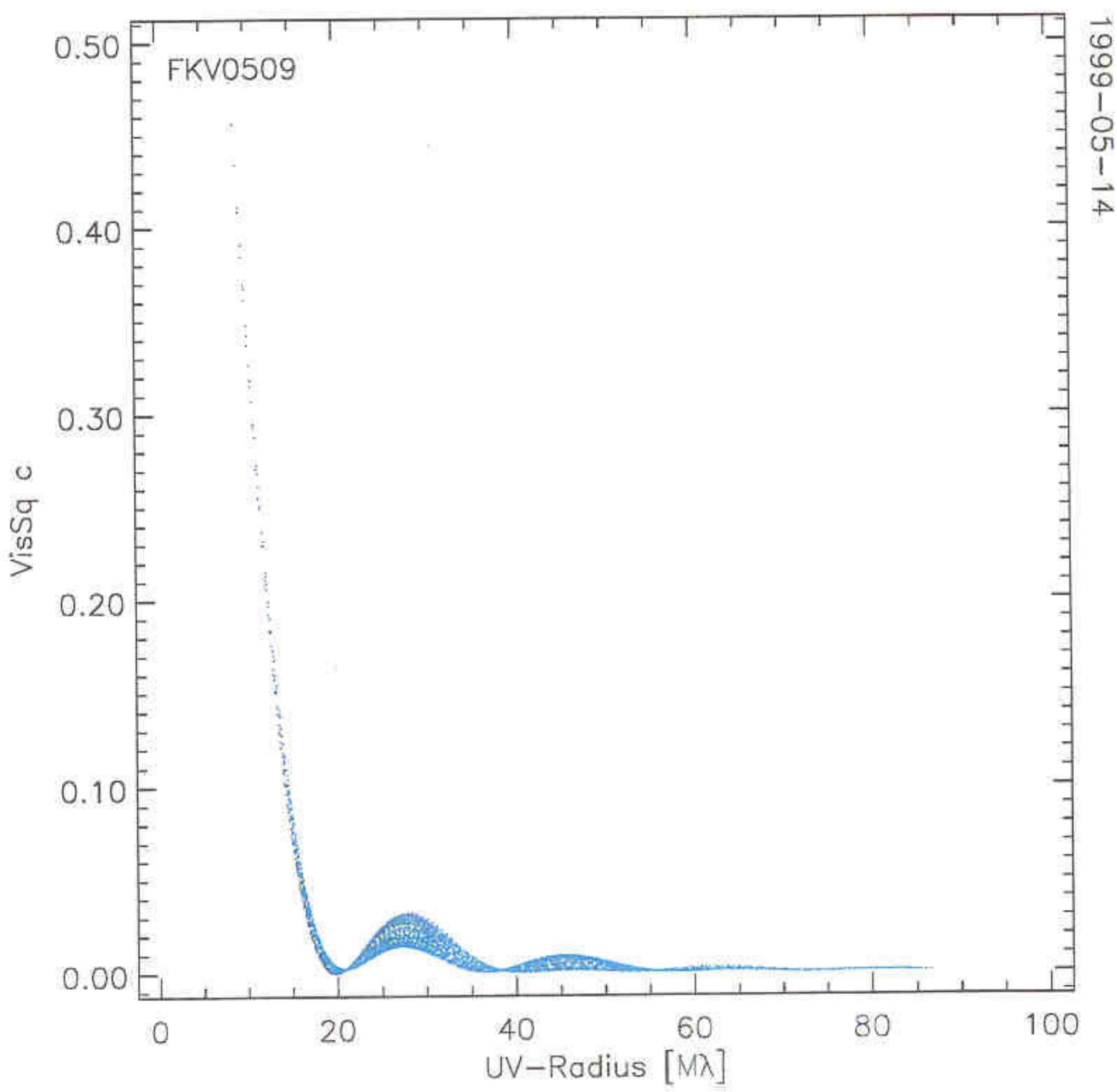
9 scans

32 spectral channels (450 - 850 nm)

noise added

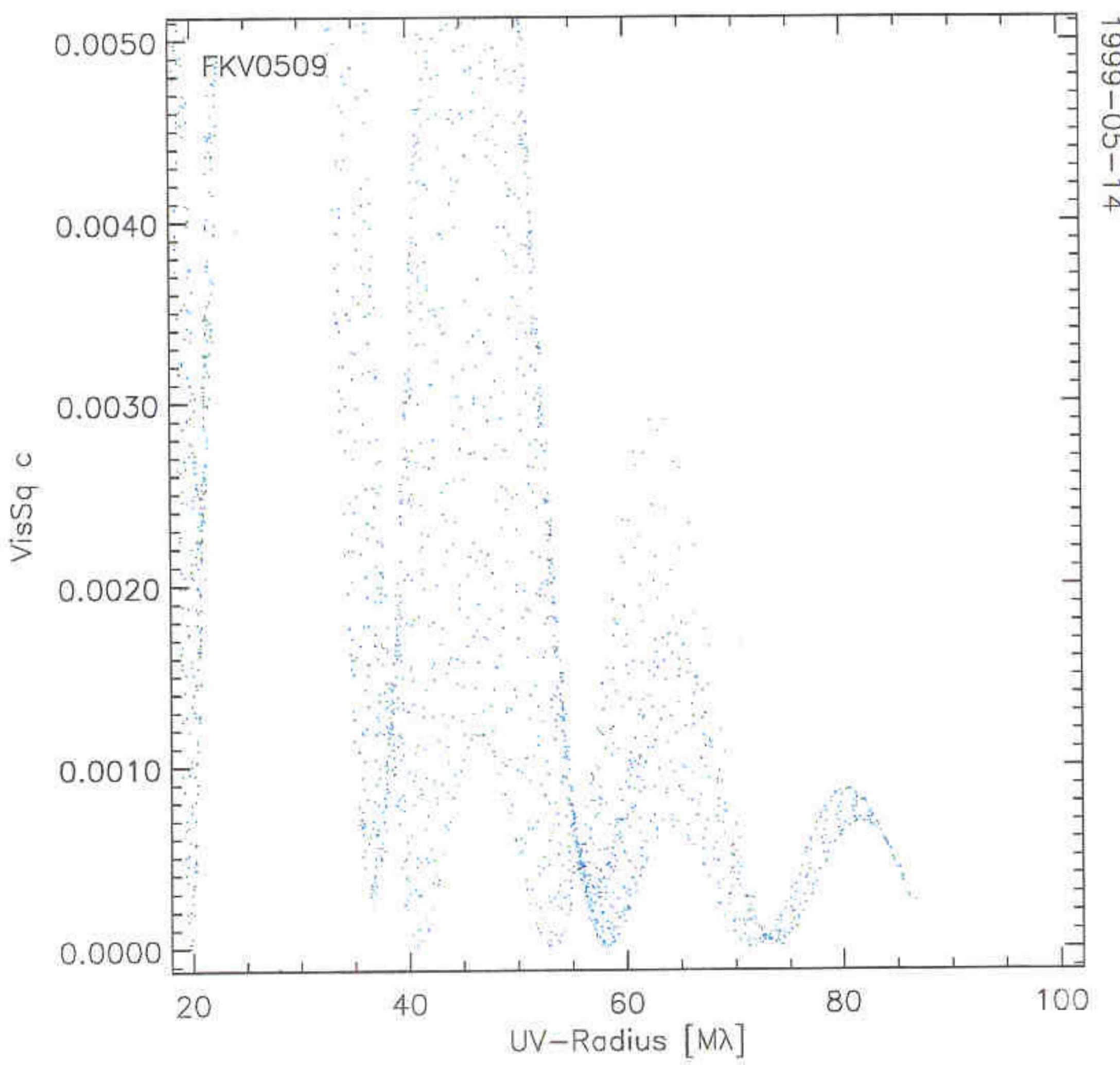


OB: 1 2 3, Bl: 1 2 3 4 5 6, Ch: 1–32



TA2

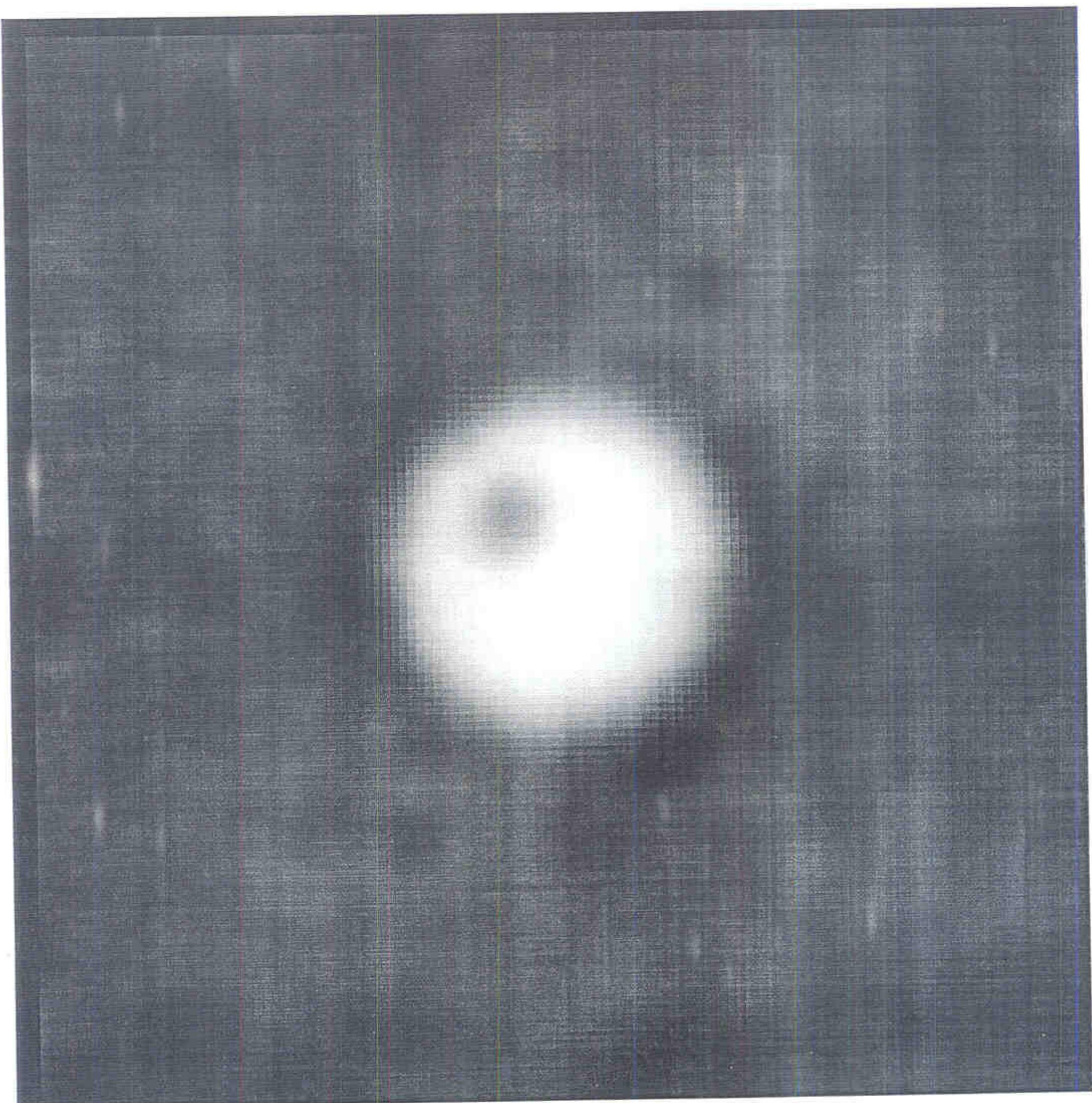
OB: 1 2 3, Bl: 1 2 3 4 5 6, Ch: 1–32



TA 28

SIMULATION 6 elements \times 32 channels \times 9 scans

Maximum Entropy Reconstruction



TA 21

Themes

- The low S/N data are where the interesting science is.
- Multiwavelength capability provides many benefits.

A sampler of astrophysics

- Observe surface features; watch stars rotate
- Measure limb darkening to check stellar atmosphere models
- Calibrate the effective temperature scale
- Measure Cepheid pulsations to get direct distance measurements
- Observe circumstellar material
- Image interacting binaries